APPLICATION OF THE HVEEM STABILOMETER TO THE TESTING OF OPEN-GRADED BITUMINOUS MIXTURES

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by
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Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Final Report

APPLICATION OF THE HVEEM STABILOMETER TO THE TESTING

OF OPEN-GRADED BITUMINOUS MIXTURES

TO:	K. B. Woods, Director Joint Highway Research Project	July 1, 1959
FROM:	H. L. Michael, Assistant Director Joint Highway Research Project	File: 2-4-17 Project: C-36-6Q

Attached is a final report entitled, "Application of the Hveem Stabilometer to the Testing of Open-Graded Bituminous Mixtures," by R. A. Hannan, Graduate Assistant on our staff. Mr. Hannan utilized this research reported as a portion of the requirements for the MSCE. The research was performed under the direction of Professor W. H. Goetz.

Mr. Hannan while performing the major portion of this research received a fellowship from the National Sand and Gravel Association. He was employed by the Project for only the last few months of the research. Laboratory facilities, extra labor and some supplies were also furnished by the Project.

The report is presented for the record.

Respectfully submitted,

H. L. Michael

H. L. Michael, Secretary

HLM:jt

Attachment

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Purdue University
Lafayette, Indiana

July 1, 1959

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This study was conducted at Purdue University under a fellowship financed by the National Sand and Gravel Association. The author wishes to express his appreciation to this organization and to Mr. Stanton Walker, its Director of Engineering, for their valuable assistance.

The writer will always be indebted to Professor William H. Goetz, Research Engineer of the Joint Highway Research Project and Professor of Highway Engineering at Purdue University. It was Professor Goetz' constant guidance and support that made the completion of this study possible.

Special thanks are also due the Joint Highway Research Project, Purdue University, for financing the final portion of the study and providing the laboratory facilities, equipment, materials, and part-time student help needed for the project.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

ABSTRACT

Hannan, Robert A., M.S.C.E., Purdue University, August, 1959. APPLICATION OF THE HVEEM STABILOMETER TO THE TESTING OF OPEN-GRADED BITUMINOUS MIXTURES. Major Professor, William H. Goetz.

This laboratory investigation was conducted with the purpose of determining the applicability of the Hveem Stabilometer to the testing of open-graded bituminous mixtures.

The study was divided into two major sections. The first of these investigated the validity of the Stabilometer displacement measurement when applied to open-graded specimens having large surface air voids. The second portion of the study had two specific purposes: (1) to investigate the stress-strain characteristics of open-graded mixtures tested in the Hveem Stabilometer and (2) to determine whether surface voids on the ends of Stabilometer test specimens influenced Hveem stability values.

To check the validity of the displacement measurement, Stabilometer tests were conducted over a wide range of displacement values for duplicate specimens molded from three different mixtures. Displacement readings were varied by altering the surfaces of test specimens and by adjusting the quantity of air inside the Stabilometer oil chamber.

In studying the stress-strain characteristics of open-graded mixes, Stabilometer values and specimen deformation readings were obtained for two mixtures. The first of these open-type mixes was

well-graded, but the second was essentially "one-sized" in gradation.

Results of this investigation showed that the final displacement value, when substituted into the Hveem stability equation, did not compensate for the variations in lateral pressure caused by large changes (one or more turns) in the final displacement measurement.

Stress-strain relationships for the well-graded, open-type mixture indicated that the quantity of strain permitted a Stabilometer test specimen conformed closely with the amount of strain developed at the maximum shearing strength of a rational triaxial test specimen subjected to confining pressures similar to those present in a Stabilometer test.

Strain measurements recorded for Stabilometer specimens of the one-sized mixture used in this study were much lower than those obtained at the peak value of shearing resistance for triaxial test specimens of the same mixture and for similar confining pressures.

Surface air voids on the ends of Stabilometer test specimens had a small effect on test results. When these voids were filled, Hveem stability values were not significantly higher, but the reproducibility of test results was greatly improved by coating test specimens.

To improve the consistency of Stabilometer test results obtained from open-graded mixtures, certain modifications in the testing technique were suggested. These changes involved the filling of air voids on the surface of test specimens and the admittance of an increased amount of air in the Stabilometer oil chamber during the calibration of the testing apparatus.

INTRODUCTION

The stability of a bituminous pavement may be defined as the pavement's ability to resist lateral deformation when subjected to normal traffic loads. Several laboratory tests are currently used for measuring the stability of bituminous paving mixtures. Among these, the Hveem stabilometer test is rapidly growing in popularity. Originated by Francis N. Hveem of the California Division of Highways, this test has now been adopted by several other agencies, including the Indiana State Highway Department.

Under Hveem's method of mix design, the Stabilometer is used in conjunction with the Hveem Cohesiometer. The Stabilometer is primarily a measure of that part of the specimen's resistance which is due to the friction developed between aggregate particles. The Cohesiometer test accounts for the mix's tensile strength, or cohesion. Although the Cohesiometer is employed, the Stabilometer does measure the total shearing resistance of the specimen. The short test specimen used in the Stabilometer tends to exaggerate the frictional component of the mix's strength, and the Cohesiometer is added merely to obtain an indication of the specimen's cohesive resistance (9)*.

The Stabilometer has distinct advantages over other stability tests. It is quick and easy to run, and may be used for field control purposes as well as for the laboratory design of bituminous mixes.

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* Numbers in parentheses correspond to references listed in the bibliography.

The Stabilometer also affords the specimen a lateral confinement similar to that provided the loaded portion of an actual pavement. The main criticism of the test is that it presents an empirical rather than a rational approach to the design of mixtures. This is true of all current design procedures, however, and until more is learned about the subject, the Stabilometer will continue to play an important role in the field of pavement design.

In this report, any well-graded mixture containing material down to, and passing, the No. 200 mesh sieve is considered to be "dense-graded." A mixture containing no material finer than the No. 200 mesh is "open-graded." Despite the availability of a vast amount of data correlating Stabilometer results with field performance, very little work has been done with open-graded mixtures. Concerning this, The Asphalt Institute (21) states, "To date, the Hveem Method has been used principally for the design of dense paving mixtures."

For several years, the Indiana State Highway Department has had considerable success paving primary roads with open-graded mixtures of bituminous concrete. In fact, many of these pavements have performed more satisfactorily than those made with dense mixtures. In order to obtain a more thorough analysis of open-graded mixtures, however, a laboratory test procedure is needed which will provide a realistic stability measurement for this type of mix. The purpose of this study, then, was to determine what modifications, if any, are necessary should the Stabilometer be used to test open-graded mixes. Although time did not permit an extensive correlation between field performance and Stabilometer results for these mixes, it is felt that the study

did bring out limitations in the present test procedure which until now, have not been given proper consideration.

REVIEW OF LITERATURE

The preparation of this study necessitated the review of several technical papers dealing with the design of bituminous mixtures. When written, each of these had a valid contribution to make on the subject. Much of this work, however, does not directly pertain to the phase of mix design encompassed by this report. Therefore, this review will include only that subject matter which is essential to a basic understanding of the following topics:

1. Operations of the Hveem Stabilometer.
2. Effect of Air on Test Results
3. Interpretation of Test Results
4. The Stabilometer Specimen

Operation of the Hveem Stabilometer

Since its inception by Hveem several years ago, the Stabilometer has undergone many revisions. As a result, the test methods utilized by some agencies (9, 10) differ from the procedure advocated by Hveem. Moreover, Hveem's method of test for soils (5, 16, 20) is quite unlike the test he uses for bituminous mixtures. All methods, however, have the same basic approach, and the technique discussed here will be that currently specified for the testing of bituminous mixtures by Hveem and the California Division of Highways (6, 20, 21). A detailed description of Hveem's method is included in the portion of this

report entitled "Procedure."

The Stabilometer test is essentially a "closed" system triaxial compression test based upon the "... conclusion that the ability to resist lateral displacement is a characteristic of stable bituminous pavements" (6). As shown in Figure 1, a cylindrical specimen is confined laterally by a rigid cell. The boundary between the confining mixture and the specimen consists of a flexible rubber diaphragm. When loaded axially, the specimen is deformed outwards against the diaphragm, causing a reduction in the volume occupied by the confining fluids. As a result of this volume reduction, a pressure is created in the system that provides the specimen with the lateral support characteristic of all triaxial tests. The effects of this lateral confinement have been widely discussed in the literature (3, 4, 6, 12, 13, 14).

The magnitude of the transmitted pressure in the Stabilometer can be interpreted as an inverse measure of the specimen's stability (6). For any given vertical load, a weak specimen will give higher lateral pressures than a strong one because of the weak mixture's greater tendency to deform. Using this observation as the basis for his test, Hveem records the lateral pressure transmitted under a 400 psi vertical load to measure the stability of a bituminous mixture.

Effect of Air on Test Results

Since the transmitted lateral pressure depends upon the volume reduction of the confining fluids, air and oil, in the Stabilometer system, the differing compressibilities of these fluids must be taken into consideration. For the temperature and pressure conditions of

DIAGRAMATIC SKETCH OF THE HVEEM STABILOMETER

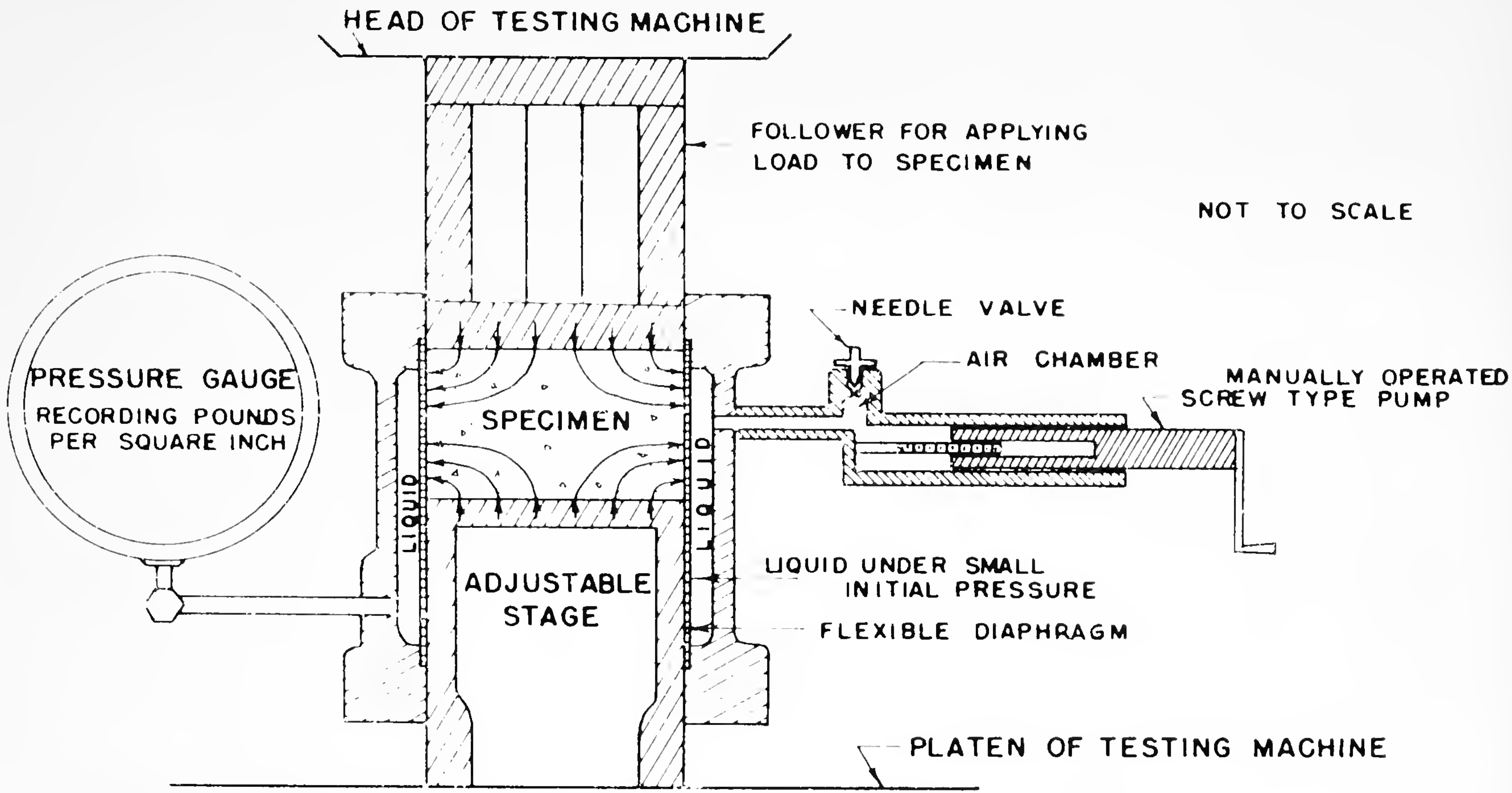

FIG. 1

After California (20)

this test, the compressibility of oil is negligible. Air, however, is easily compressed and relatively large changes in volume can occur without appreciable changes in pressure. From this observation, any volume reduction in the confining medium is evidently a reduction in the volume occupied by the air. Also, small increases in the air content of the system will permit greater specimen deformations without compensating increases in lateral pressure.

Because of the critical influence of air content on test results, Hveem attempts to control this variable with a "displacement" measurement (6, 16). At the start of each test, the amount of air inside the Stabilometer cell is calibrated using a dummy metal specimen and the displacement pump shown in Figure 1. The correct air content is indicated when two revolutions of the displacement pump will increase the lateral pressure reading from 5 to 100 psi. This measurement is termed the "initial displacement" and actually measures the volume reduction created in the system when the lateral pressure is increased from 5 psi to 100 psi. An initial displacement of two turns was adopted by Hveem because the significance of test results was impaired when lower displacement values were used (6).

In addition to the air inside the Stabilometer cell, the air between the rubber diaphragm and the specimen will cause variations in the lateral pressure (6, 10, 16), since during a test "... the specimen becomes in effect an integral part of the Stabilometer system..." (6). Recognizing this influence of the specimen's surface air voids, Hveem incorporates a "total displacement" measurement. This reading, taken at the end of every test with the bituminous specimen

held in place by a 1000-pound vertical load, accounts for the air in the surface voids of the specimen as well as the air inside the Stabilometer cell. On this subject, Hveem and Davis (6) stated:

> While in a sense the displacement value is a correction for the test specimen itself, fundamentally it is a correction for the entire Stabilometer system as air voids anywhere in the system will have the same effect on the instrument reading.

To the author's knowledge, Hveem's method of correcting for surface air voids is currently the only one in use. In 1947, McCarty (10) of the Texas Highway Department proposed a method of correction based on empirical relationships between Stabilometer gage pressure, final displacement, and the volume of specimen surface voids. This procedure did not gain general acceptance, however, and a later publication by McCarty (9) outlined Texas' Standard Method of Test which is essentially the same as the one used by Hveem.

Interpretation of Test Results

For the purpose of reporting test results, Hveem employs the following empirical formula (6, 8, 10, 20, 21):

$$S = \frac{22.2}{\dfrac{P_h D_2}{P_v - P_h} + 0.222}$$

where: S = Hveem stability

P_v = vertical pressure = 400 psi

P_h = lateral pressure corresponding to P_v = 400 psi

D_2 = total displacement on specimen

As implied above, the stability of a bituminous mixture tested

in the Stabilometer is based upon the lateral pressure transmitted under a vertical pressure of 400 psi. This vertical load is assumed to be "... reasonably representative of the stresses developed by pneumatic tired truck traffic (recognizing the increase of static load due to so-called impact)"(18). Hveem and Davis (6) stated that the selection of this load is an attempt to account for the cumulative effects of traffic that occur with time. Since 100 psi is the usual maximum tire pressure developed on highways, McCarty (9) surmised that Hveem's choice of the 400 psi tire pressure was made to introduce a safety factor of four with respect to static load.

The total displacement on the specimen is added to the stability equation such that an increase in displacement will lower the computed stability value. This, of course, is an attempt to compensate for the decrease in lateral pressure which accompanies increased air contents. The equation established by Hveem for reporting the stability of bituminous mixtures is based solely on correlation data. An arbitrary stability scale was selected in which a value of 0 represents a liquid with no resistance and where 100 is a rigid solid that will not deform under load (5, 16, 18). Experience has shown that bituminous mixes with stability numbers lower than 30 or 35 generally give unsatisfactory field performance (6, 18, 20, 21).

The available literature does not clearly describe Hveem's technique in establishing the hyperbolic equation that is now used for computing the stabilities of bituminous mixes. McCarty (9) points out that even though the equations for soils and asphaltic mixtures differ, both can be reduced to the following relationship:

$$R \text{ (or S)} = 100 \left(\frac{P_v - P_h}{P_v - P_h(1 - \frac{D}{D_o})} \right)$$

where: D = measured displacement

D_o = 0.222 for bituminous mixes and 2.5 for soils

In analyzing this equation, McCarty states:

> The parameters D and D_o are functions of specimen deformation, called displacements, D_o being a base value so chosen in relation to observed average values of D as to make the index range correspond with the strength range for typical road materials in place.

Monismith (11) states that Hveem's stability equation was originally a linear relationshipbetween lateral pressure and stability, and that the present hyperbolic relationship is purely an arbitrary selection made to increase the range of stability values between good and poor mixes. With the original linear relationship, a large portion of the stability scale was occupied by unrealistic mixes of either very high or very low strength.

The Stabilometer Specimen

The test specimen used in the Stabilometer is a cylinder 2-1/2 inches high and 4 inches in diameter. According to Hveem and Davis, "... the height of the specimen was selected to correspond to the typical thickness of bituminous surfacing commonly used in highway work..." (6). Although the size of the specimen does facilitate the testing of cored pavement sections, the low height to diameter ratio makes a theoretical analysis of test results difficult. Triaxial-test studies conducted by Smith (17) indicate that a height to diameter

ratio greater than 2.0 is desirable for the determination of cohesion, C, and angle of internal friction, ϕ. This ratio for a Stabilometer specimen is well below that figure.

Also on the subject of specimen height, McCarty (9) states:

> Thus, while it is not correct to base the design of comparatively thick base courses on results from a Hveem Stabilometer test on a small Hveem specimen without applying a height correction derived experimentally from theory, if possible, for the relatively great difference in structural strength, neither is it correct to apply uncorrected results from the test on a tall specimen in the design of thin bituminous-surface courses.

The preparation of realistic test specimens is essential to the correlation of laboratory and field properties of bituminous mixtures (6). Hveem's method of fabricating Stabilometer specimens employs the mechanical compactor developed by the Triaxial Institute. This compactor was designed to mold a laboratory specimen possessing the density and stability corresponding to a pavement after one year of service (7, 22). In describing the action of a kneading compactor, Endersby (4) states:

> The material is fed into a rotating mold and kneaded into place by a tamping foot of the general shape of a slice of pie with rounded corners.
>
> This foot descends with a rather slow motion in order to avoid impact and has a short "dwelling period" at the bottom of the descent in order to overcome viscosity. It operates under a constant load, the low point of the descent being automatically raised as the material rises in the mold. The specimen is finished off by a smoothing load when completed.

Although California uses the kneading compactor, it should be noted that Stabilometer specimens can be prepared by other means. For example, the Texas Highway Department has adopted a Gyratory Shear Method which also attempts to simulate field densities and stabilities

(9, 15). The advantages and disadvantages of various compaction procedures is beyond the scope of this paper, however, and will not be presented here.

PURPOSE AND SCOPE OF THE INVESTIGATION

The overall purpose of this study was to determine the applicability of the Hveem Stabilometer to the testing of open-graded bituminous mixtures. To attack this problem, the investigation was divided into two major sections:

1. Because of the deficiency of fine material in open-graded mixtures, Stabilometer specimens made from this kind of mix will usually have surface air voids which are greater in both size and number than the voids present in dense-graded specimens. Consequently, Stabilometer tests on open-graded specimens will result in high displacement numbers which tend to vary widely from specimen to specimen. Because of this situation, the major portion of this study was designed to check the validity of the displacement measurement when applied to open-graded mixes.

2. The second part of this study was twofold in purpose:

   a. As the void ratio of a granular mixture is increased, more strain is required to develop the mix's maximum shearing resistance. Since the Stabilometer limits the amount of strain which a specimen can undergo, one purpose was to investigate the stress-strain characteristics of open-graded specimens tested in the Hveem Stabilometer.

   b. The final portion of this project was a short check to see if the size or the number of voids on the ends of the Stabilometer specimen have an effect on test results. Although these voids do not

influence the displacement number, they do reduce the effective area over which the axial load is applied and would appear to cause a greater unit stress in the vertical direction.

MATERIALS

The materials used in this study were asphalt cement, crushed limestone, uncrushed gravel and natural sand. A detailed description of these materials is presented in the following discussion.

Mineral Aggregate

Aggregates for the project were secured from two commercial plants. The crushed limestone was provided by the Ohio and Indiana Stone Company of Greencastle, Indiana, and the uncrushed gravel and natural sand were obtained from the Western Indiana Sand and Gravel Company of Lafayette, Indiana. Table 1 shows the specific gravity and absorption values for each of these aggregates.

TABLE 1

Physical Properties of Aggregates

Aggregate	Bulk Sp Gr	Apparent Sp Gr	% Absorption
Crushed Limestone	2.60	2.67	1.13
Uncrushed Gravel	2.61	2.75	2.00
Natural Sand	2.57	2.68	1.56

Bituminous Material

The binder material in each of the four mixtures was a 60-70 penetration grade asphalt cement. This material was furnished by the Texas Company of Port Neches, Texas, and possessed the physical properties shown in Table 2.

TABLE 2

Physical Properties of Asphalt Cement

Test	Results
Penetration - 1/100 cm ($77^\circ F$, 100 gm, 5 sec)	66
Specific Gravity ($77^\circ F/77^\circ F$)	1.031
Ductility - cm ($77^\circ F$, 5 cm/sec)	200+
Solubility in CCl_4 - %	99.92

PROCEDURE

In collecting data for this investigation, the utilization of a large amount of laboratory apparatus and equipment led to a variety of techniques, some of which became quite involved. With this in mind, the writer feels that a detailed discussion of these procedures in this section would only tend to cloud their overall objectives. Hence, the techniques discussed here include only those needed to provide an understanding of the general approach to the problem. Appendix A, entitled "Apparatus and Detailed Procedures" has been added to supplement this information.

The procedures outlined in this section are grouped as follows:

1. Fabrication of Test Specimens
2. Hveem Stabilometer Tests
3. Data Reduction

Fabrication of Test Specimens

Hveem Stabilometer specimens of four different aggregate gradations were formed in this study. For the sake of convenience, these mixtures have been denoted as A, B, C, and D. Each grading is tabulated in Table 3, and is graphically illustrated in Figure 2. The asphalt contents, by weight of mix, are listed in Table 4.

Grading A was an open-graded mixture in that it included no mineral aggregate finer than the No. 200 mesh sieve. It consisted of uncrushed

TABLE 3

Sieve Analyses for Aggregate Mixtures

(Percent by Weight)

Sieve Size		Percent Between			
Passing	Retained	A	B	C	D
--	3/4"	0	0	0	0
3/4"	1/2"	17.5	25	0	29.2
1/2"	3/8"	21.4	25	0	35.4
3/8"	#4	21.4	6.5	16	35.4
#4	#8	4.6	27.5	18	0
#8	#16	10.5	3	14	0
#16	#30	10.4	5	12	0
#30	#50	10.3	5	14	0
#50	#100	3.6	2	10	0
#100	#200	0.3	1	8	0
#200	----	0	0	8	0

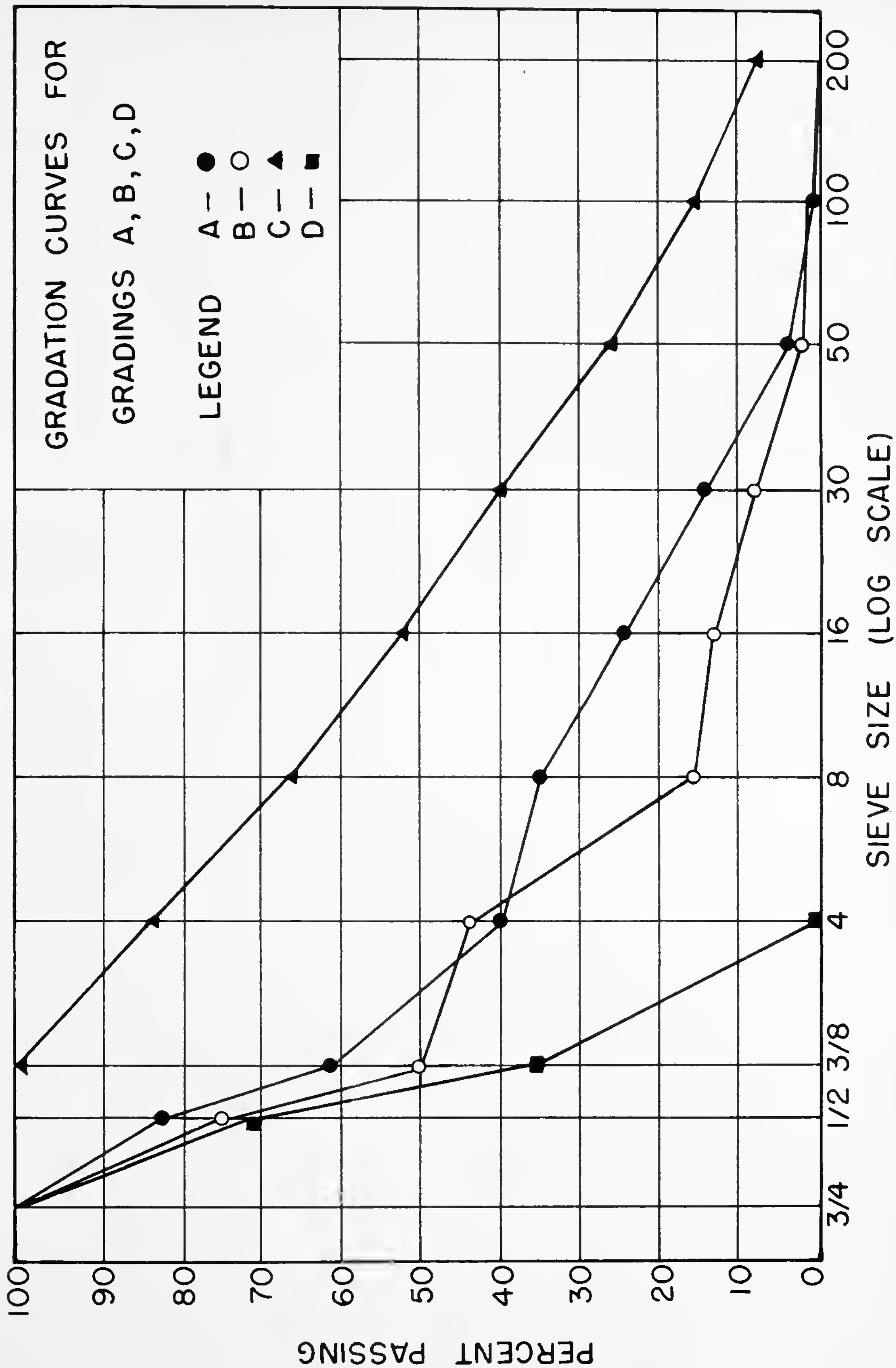
GRADATION CURVES FOR
GRADINGS A, B, C, D
LEGEND
A — ●
B — ○
C — ▲
D — ■
PERCENT PASSING
100
90
80
70
60
50
40
30
20
10
0
3/4
1/2
3/8
4
8
16
30
50
100
200
SIEVE SIZE (LOG SCALE)

FIG. 2

TABLE 4

Asphalt Contents for Various Aggregate Gradations

Aggregate Gradation	Asphalt Content Percent of Total Weight of Mix
A	5.0
B	5.0
C	5.0
D	4.0

gravel and natural sand, and was combined with 5% asphalt, by weight of mix. This mix also was used in the triaxial studies by Oppenlander (12), and by Oppenlander and Goetz (13, 14). Stabilometer specimens made from this mixture were molded by a double-plunger method of compaction. After mixing the asphalt and aggregate in the desired proportions, a mix was placed in a heated mold in two equal layers. Each layer was rodded 40 times with a 5/8-inch diameter steel rod. The rodded mix was then subjected to a 2170 psi static load for a period of a minute. During the application of the static load, both the upper and lower loading pistons were free to move vertically so as to produce equal compactive efforts at each end of the specimen. After reaching room temperature, the specimens were extruded from the molds and readied for testing.

Grading B, another open-graded mixture, combined crushed limestone and natural sand with 5% asphalt. This gradation meets the specifications for Indiana's Type A, coarse-textured surface mix (19). The method of compaction used here was identical to that used for mixture A.

Grading C was a very dense mixture selected from the U. S. Army, Corps of Engineers Specifications (2) for surface courses constructed with a 3/8-inch maximum size aggregate. Specimens made from this mix consisted entirely of crushed limestone mixed with 5% asphalt cement. A newly-acquired mechanical kneading compactor (Figure 3) was used to form these specimens and except for a few minor changes brought out in Appendix A, the procedure followed was that recommended by California (20).

Grading D was the "one-sized" mix used in the work by Oppenlander (12), and Oppenlander and Goetz (13, 14). For this investigation,

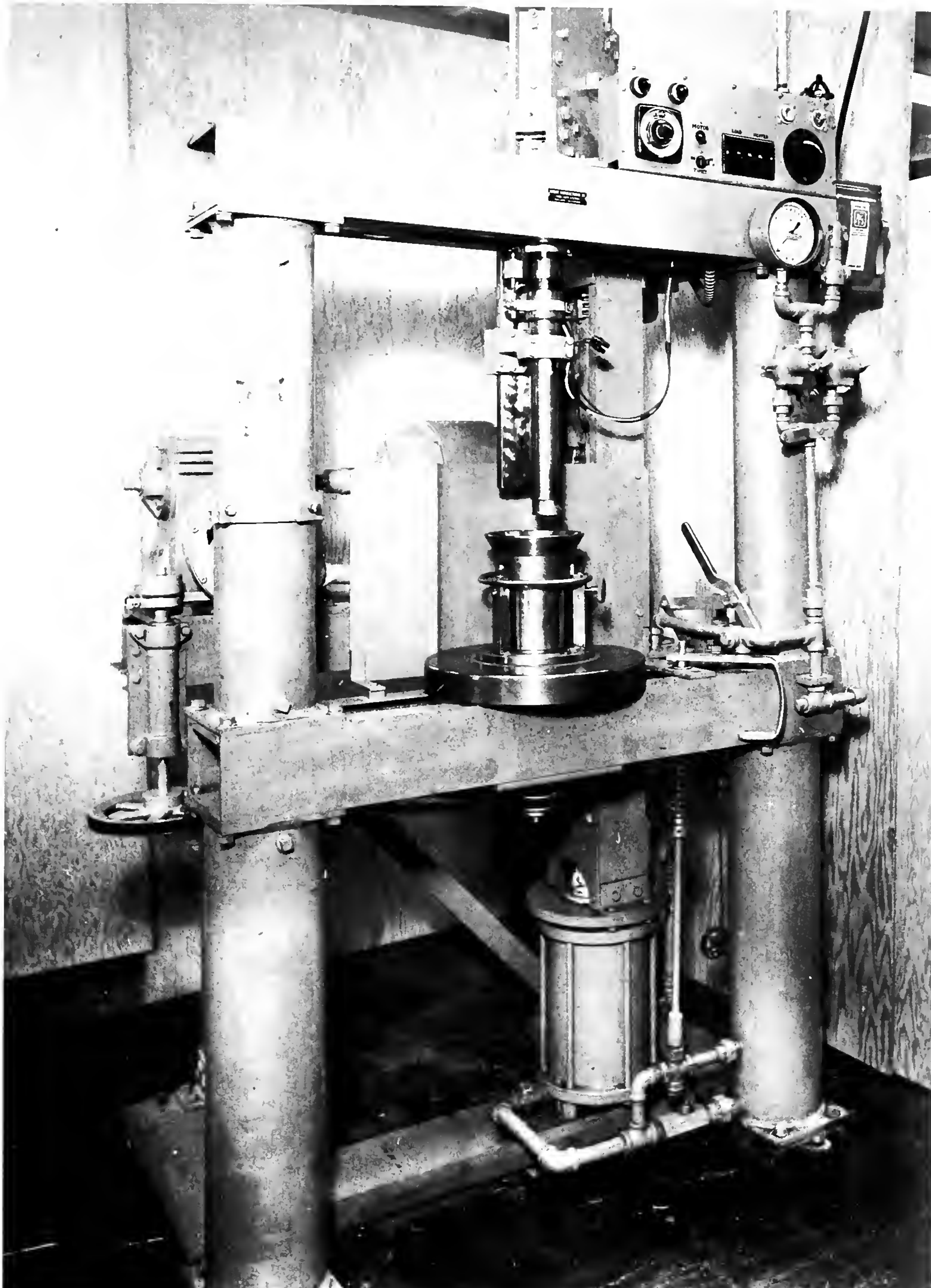

FIG. 3 MECHANICAL KNEADING COMPACTOR

uncrushed gravel was mixed with 4% asphalt. Because of the lack of fine aggregate in this gradation, attempts to compact the mixture with the kneading compactor resulted in excessive aggregate fracture. For this reason, a combined vibratory-double plunger method of compaction was adopted. Under this procedure, the material was placed in the mold in two layers and rodded 40 times per layer with a 5/8-inch steel rod. The rodded mix was then placed in the compaction frame pictured in Figure 4. After applying a vertical seating load of 600 pounds, the vibrator was started and the load raised to 12,600 pounds. This load was held constant for one minute. Because of the nature of a specimen made from grading D, it was necessary to provide confinement for the molded specimen in order to avoid pre-test slumping.

Hveem Stabilometer Tests

As stated earlier, this investigation can be divided into two major divisions. The first part was set up to check the validity of the Hveem Stabilometer displacement measurement when obtained from specimens having surface air voids of considerable size and number. In this, the major portion of the study, Stabilometer tests were conducted on specimens molded from mixtures A, B, and C. The second section of the project was later added to investigate the influence of specimen deformation and effective vertical stress on the Hveem Stability number. The discussion of the procedures used to conduct Stabilometer tests in this study is subdivided into these two major divisions.

Evaluation of the Displacement Measurement

The displacement measurement is, in reality, an approximate

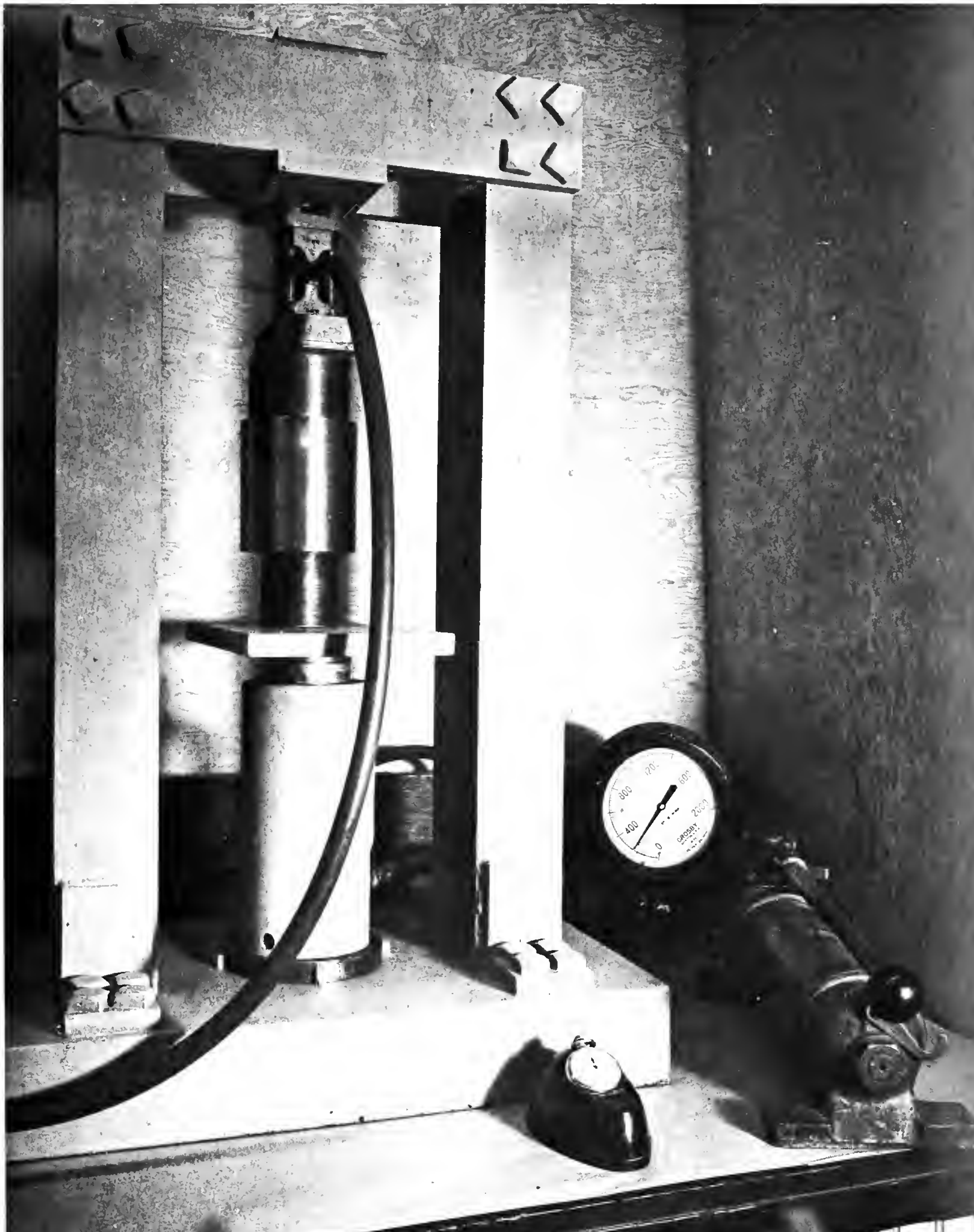

FIG. 4 VIBRATORY COMPACTION APPARATUS

correction for the air which is compressed in the system of a Stabilometer test. To determine the validity of this measurement for specimens with large air voids, then, the most logical approach to the problem was to test specimens of equal strength in the Stabilometer at a variety of air contents. If these tests gave Hveem Stability values of equal magnitude, the use of the displacement value would be ascertained correct for specimens with large surface voids.

In investigating the displacement number, two methods were used to vary the amount of air present in the system of the different Stabilometer tests. The first procedure was to control the surface characteristics of each specimen in one of the following three ways:

1. Air voids on the lateral surface of the specimen were filled by coating the surface with a paste made from plaster of paris, portland cement, and water.
2. Holes were drilled on the surface of the specimen to introduce additional air into the system.
3. The surface was left unaltered so that the voids present during the test were those actually formed during the compaction of the specimen.

The specimens shown in Figure 5 typify those used in this phase of the investigation.

The possibility of a reduction in the strength of a specimen due to the drilling of simulated surface voids limited the range of air contents which could be obtained by this method. As a result, this procedure was used only for a few specimens made from mixture A, and a second method was devised for controlling the air in the system of a

FIG. 5 TYPICAL TEST SPECIMENS

Stabilometer test. Under this second technique, all specimens were coated with the plaster-cement-water mixture and the air content was adjusted inside the Stabilometer oil chamber rather than on the surface of the specimen. This procedure permitted a wider range of air contents and much better control over the displacement values than was possible with the original approach.

To vary the amount of air inside the oil chamber of the Stabilometer, the instrument was calibrated at initial displacement readings of 1.00, 2.00, 3.00, 4.00, and 5.00. Several Hveem Stabilometer tests were then conducted at each of these displacements for mixtures A, B, and C.

To provide better control over test conditions, all tests were performed at room temperature, rather than at the 140°F temperature specified by Hveem. Also, because deformation measurements were recorded during tests on mixture A, a 10,000 pound proving ring and a deflection dial were added to the apparatus. Stabilometer gage pressures and deformation readings were then taken at vertical load increments of 250 pounds. For tests on mixtures B and C, deformation values were not included in the test procedure, and lateral pressure readings were taken at vertical loads of 500, 1000, 2000, 3000, 4000, 5000, and 6000 pounds. In this instance, the proving ring was not used, but vertical loads were measured directly from the testing machine's calibrated beam.

Figure 6 shows the complete assembly for a Hveem Stabilometer test in which deformation readings were taken.

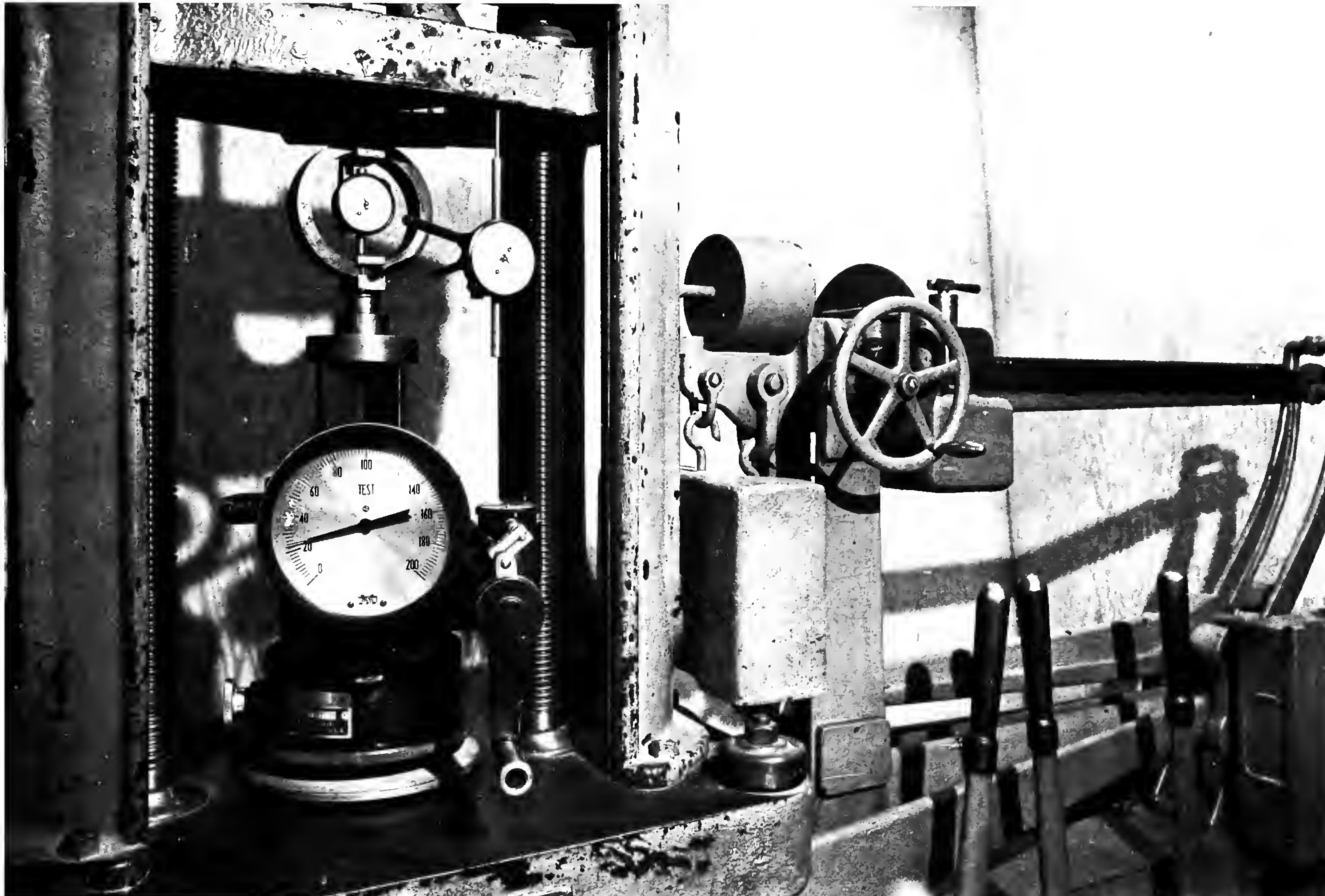

FIG. 6 HVEEM STABILOMETER TEST WITH STRAIN MEASUREMENTS

Influence of Vertical Stress and Specimen Deformation on Hveem Stability

The second portion of the investigation was approached with two objectives in mind. First, it was desired to investigate the stress-strain characteristics of Stabilometer test specimens. The second objective was designed to tell whether the presence of large voids on the ends of the test specimen caused a significant decrease in measured strength due to the reduced effective area over which the vertical load was applied.

Although strain values were already available for mixture A, it was felt that this information should be supplemented with data from specimens representing a more extreme type of open mix. Therefore, grading D, which is essentially a "one-sized" mixture, was added to the study. Since specimens made from mixture D contained a very large number of voids, this gradation also was used to determine the effect of surface voids on vertical stress.

It was earlier stated that the final displacement values for specimens of gradings A, B, and C were controlled by coating the specimens with a mixture of cement, plaster, and water. For grading D, this procedure was abandoned because of the additional strength provided the specimens when the mixture hardened. Instead, the voids were filled with a relatively stiff paste formed with water and limestone mineral filler. This method did not permit as good a control over the displacement as did the process of coating specimens with cement, but results were considered more representative of the mixture's strength.

Specimens of grading D were tested in the Stabilometer in two series. One group had the entire surface of the specimen coated with mineral filler paste, and the second series was tested with only the lateral surface voids filled with paste. The purpose of this procedure was to determine whether surface air voids on the ends of the test specimen had an important effect on test results.

For all Stabilometer tests conducted on this mixture an initial displacement of 2.00 turns was used, specimens were tested at room temperatures, and deformation values were recorded.

Data Reduction

Figure 7 shows a data sheet typical of those used for the Hveem Stabilometer tests in which deformation measurements were recorded. The deformation dial and lateral stress readings were entered into their respective columns at the time of testing.

The column headed "Corrected Deformation" was added to the data sheet to account for the errors in deformation readings due to the deflection of the proving ring with the application of the vertical load. This value was obtained by subtracting the load dial reading from the deformation dial reading. The strain was then computed by dividing the corrected deformation by the initial specimen height.

As the vertical loading of the test specimen progressed, the cross-sectional area of the specimen became greater. For this reason, computations for the vertical stress on a specimen required a correction for the surface area over which the load was applied. The method of computing the loaded area was based on the assumptions that the specimen did not undergo any volume change and that it remained cylindrical

DATA SHEET

Hveem Stabilometer Tests

Test No. 2-A-5 Date Molded 8/15/58 Surface Coated

Initial D_2 2.00 Date Tested 8/18/58 Final D_2 2.25

Specimen Ht. 2.484 Test Temp. 77°F Stability 26.1

Load Dial	Vert. Load	Deform. Dial	Corr. Deform.	% Strain	Corr. Area	Vert. Stress	Horiz. Stress	$P_v - P_h$
0	0	0	0	0	12.57	0	5.0	-5
12	250	22	21	0.85	12.68	19.7	7.0	12.7
24	500	26	24	0.97	12.69	39.4	8.5	30.9
36	750	31	27	1.09	12.71	59.0	11.0	48.0
49	1000	37	32	1.29	12.73	78.6	14.0	74.2
62	1250	42	36	1.45	12.75	98.0	17.0	81.0
72	1500	47	40	1.61	12.78	117.4	20.0	97.4
86	1750	52	43	1.73	12.79	136.8	24.0	112.8
97	2000	56	46	1.85	12.81	156.1	28.0	128.1
110	2250	60	49	1.97	12.82	175.5	32.0	143.5
123	2500	64	52	2.09	12.84	194.7	36.5	158.2
134	2750	68	54	2.17	12.85	214.0	41.0	173.0
147	3000	72	57	2.30	12.87	233.1	46.0	187.1
159	3250	75	59	2.38	12.88	252.3	50.5	201.8
171	3500	78	61	2.46	12.89	271.5	55.0	216.5
188	3750	82	64	2.58	12.90	290.7	60.0	230.7
198	4000	85	65	2.62	12.91	309.8	66.0	243.8
210	4250	88	67	2.70	12.92	329.0	70.5	258.5
222	4500	90	68	2.74	12.92	348.3	76.5	271.8
234	4750	93	70	2.82	12.93	367.4	82.0	285.4
248	5000	96	71	2.86	12.94	386.4	87.5	298.9
259	5250	99	73	2.94	12.95	405.4	93.0	312.4
271	5500	102	75	3.02	12.96	424.4	98.0	326.4
283	5750	105	77	3.10	12.97	443.3	105.0	338.3
296	6000	108	78	3.14	12.97	462.6	111.0	351.6

FIG. 7. TYPICAL DATA SHEET.

throughout the test. Using these assumptions, then, the cross-sectional area at any point in the test was found by dividing the initial area of the specimen by a quantity equal to one minus the strain at the point in question. The vertical stress was computed as the vertical load divided by the corresponding corrected area. The difference between the vertical stress and the Stabilometer gage pressure was entered in the final column of the data sheet.

For each test, the Hveem stability number was computed from the final displacement number and the lateral pressure corresponding to a 5000 pound vertical load.

To present the results of this study, a number of graphs were drawn. Straight line relationships were obtained by the method of least squares (1). For non-linear plots, curves were drawn through average test values.

RESULTS

The results of this investigation are presented in accordance with the following outline:

I. Evaluation of the displacement measurement.

   A. Hveem stability vs. Stabilometer displacement.

      1. Mixture A

      2. Mixture B

      3. Mixture C

   B. Stabilometer displacement vs. reciprocal of transmitted pressure.

      1. Mixture A

      2. Mixture B

      3. Mixture C

      4. Comparison of measured and theoretical relationships.

II. Influence of vertical stress and specimen deformation on Hveem stability.

   A. Per cent strain vs. deviator stress.

   B. Stabilometer displacement vs. per cent strain at a 5000-lb. load.

III. Comparison of results for specimens with coated and unaltered ends.

All data which are graphically depicted in this section are also tabulated in Appendix B.

Evaluation of the Displacement Measurement

In evaluating the validity of the displacement measurement for open-graded specimens, tests were conducted on duplicate specimens of the same mixture over a wide range of Stabilometer air contents. This was done for mixtures A, B, and C. Using the data from these tests, two methods of analysis were used to evaluate the displacement value. Each of these is discussed in this section.

Hveem Stability vs. Stabilometer Displacement

For each of mixtures A, B, and C, a graph was plotted with the computed Hveem stability as the ordinate and the final displacement as the abscissa. If the displacement measurement was a true correction for air in the Stabilometer test system, this graph should have formed a horizontal line for each mixture tested. The relationships obtained for mixtures A, B, and C are reported individually in the following discussion.

Mixture A. Two methods were used to vary the final displacement measurements for tests on specimens made from mixture A. Under the first method, all tests were conducted at an initial displacement of 2.00 turns, and the specimen surfaces were either coated, drilled, or left unaltered. Figure 8 shows the relationship between Hveem stability and final displacement for each of these tests. As the final displacement values were increased, the computed Hveem stability numbers did not remain constant, but decreased appreciably.

Although the slope of the line in Figure 8 suggests an inconsistency in the displacement measurement, the variation in stability

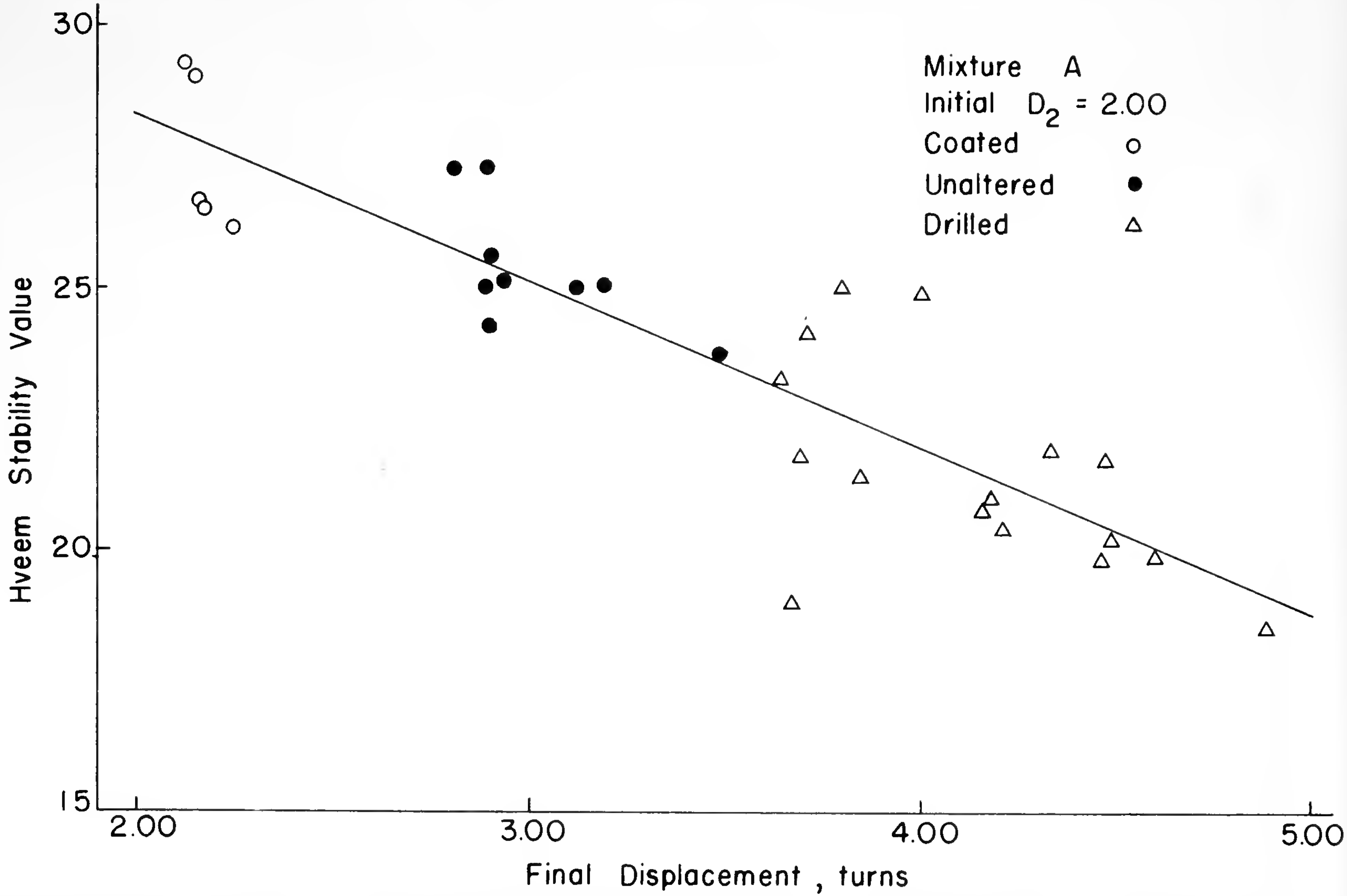

FIG. 8 HVEEM STABILITY vs FINAL DISPLACEMENT

with increased air content might also be attributed to actual changes in the strength of specimens caused by the drilling and coating of lateral surfaces. For this reason, and also to obtain a greater range of displacement values, a second method was used to vary the amount of air in the test system. Under this procedure, only coated specimens were tested, and air was adjusted inside the Stabilometer oil chamber to give initial displacement values ranging from 1.00 to 5.00 turns.

Figure 9 shows the relationship between Hveem stability and final displacement for coated specimens of mixture A. Here, as in Figure 8, increased displacement values resulted in reduced stability numbers. At high values of displacement, however, computed stability numbers were higher for the coated specimens of Figure 9 than for the drilled specimens of Figure 8. This difference probably resulted from actual variations in strength due to the drilling and coating techniques. The variable of true strength was eliminated for the relationship shown in Figure 9, since only coated test specimens were used. Hence, the observed decrease in stability for these specimens must have been due to the increased air content of the system as indicated by the displacement measurement.

<u>Mixture B</u>. Stabilometer tests on coated specimens made from mixture B were conducted at initial displacements of 1.00, 2.00, 3.00, 4.00, and 5.00 turns. Figure 10 is a plot of final displacement vs. Hveem stability for specimens of mixture B. Test results for this mixture were quite erratic, but there was a downward trend in the value of stability number when displacement values were increased. The erratic

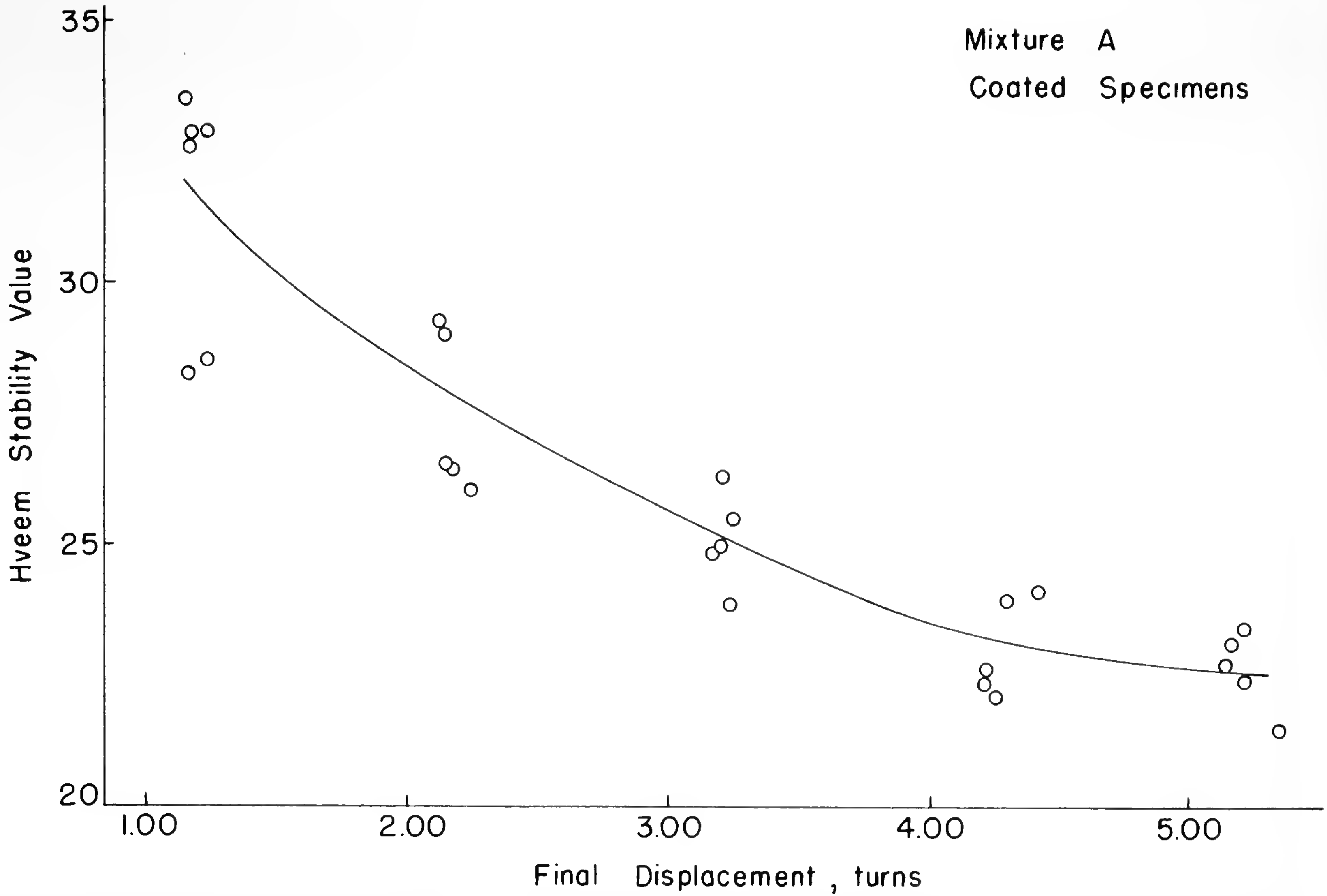

FIG. 9 HVEEM STABILITY vs FINAL DISPLACEMENT

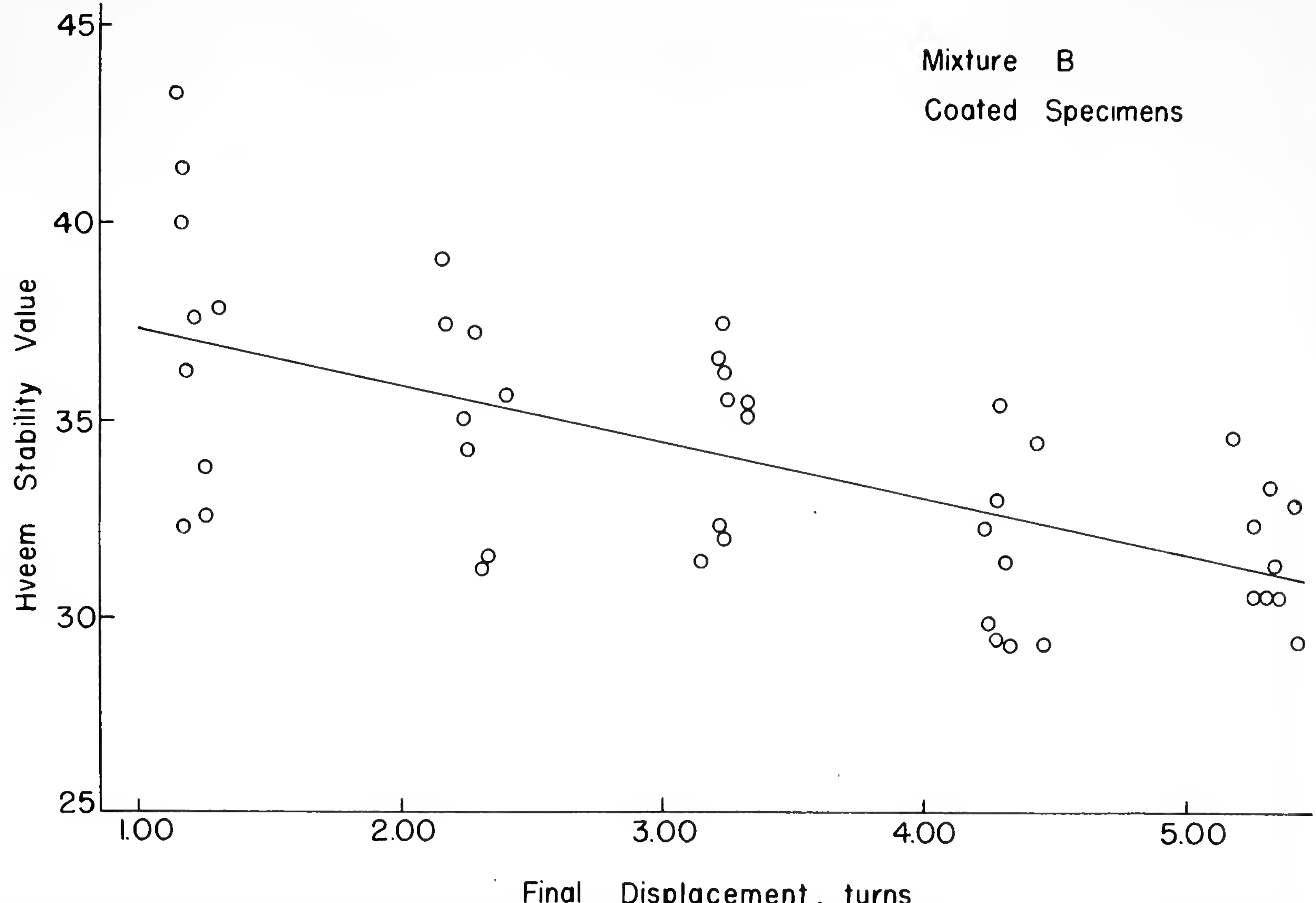

FIG. 10 HVEEM STABILITY vs FINAL DISPLACEMENT

results obtained from specimens of mixture B can probably be attributed to the segregation and arching effects of the large, angular pieces of crushed limestone contained in this mix.

Mixture C. Figure 11 illustrates the relationship between Hveem stability and final displacement for specimens of mixture C. The dense gradation of these specimens, coupled with the fact that they were molded in the mechanical kneading compactor, resulted in much higher values of stability than those which were obtained from mixtures A and B. Also, the slope of the curve of final displacement vs. stability differed for mixture C. Stabilometer tests on mixtures A and B indicated a steady decrease in measured stability when air in the test system was increased. Stability numbers for mixture C were highest at displacement values of 2.00 and 3.00 turns, but then decreased as more air was added or removed from the system.

As seen in Figure 11, the reproducibility of test results was better at higher air contents than at lower ones. For tests with initial displacement values of 1.00 and 2.00 turns, the transmitted lateral pressures were very erratic, probably because of the limited strain afforded the specimens.

Stabilometer Displacement vs. Reciprocal of Transmitted Pressure

Hveem's empirical stability equation is a hyperbolic relationship in which stability is expressed as a function of a constant (5,000 lbs.) vertical load and the final displacement measurement. By substituting stability numbers into this formula, the plot of lateral pressure versus

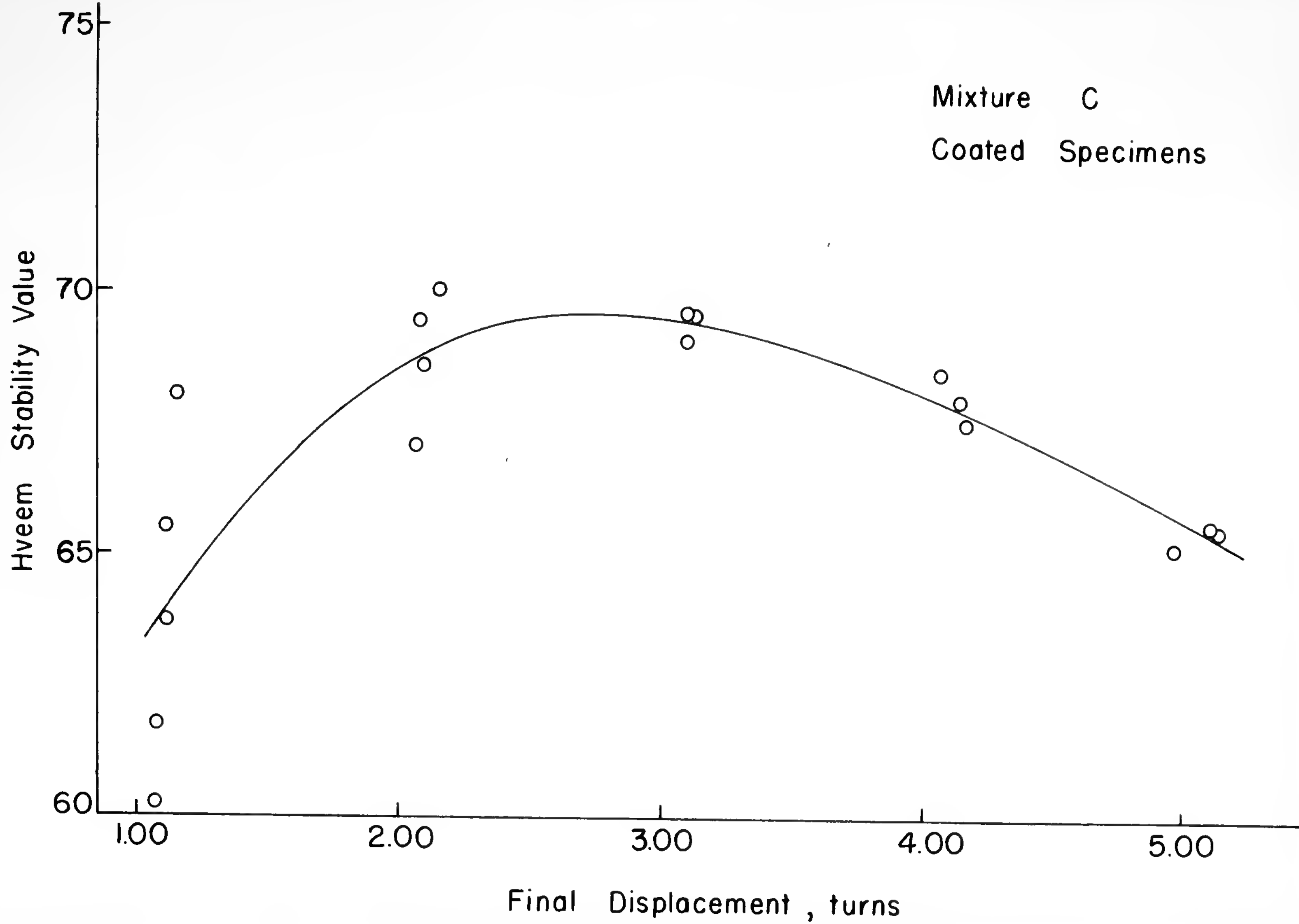

FIG. 11 HVEEM STABILITY vs FINAL DISPLACEMENT

displacement results in a family of hyperbolas. As a further simplification, the graph of final displacement versus the reciprocal of lateral pressure gives a family of straight lines for a range of hypothetical stability numbers.

In order for the final displacement measurement to be a true correction for air in the Stabilometer test system, the graph of displacement versus the reciprocal of lateral pressure for any given mixture should conform to the linear relationships obtained by substituting hypothetical values into the stability equation.

In this section of the study, the relationships between displacement and the reciprocal of lateral pressure for mixtures A, B, and C are graphed and compared to the theoretical curves.

Mixture A. Figure 12 shows the results obtained by testing coated, unaltered, and drilled specimens at an initial displacement of 2.00 turns. Because of the wide scatter in the points which represent tests on drilled specimens, as well as the strength reduction experienced by specimens when drilled, no attempt was made to fit a curve to these data. There appears to be a non-linear trend in the relationship, however, and the reproducibility of test results was very much improved when the surfaces of specimens were coated.

In Figure 13, the graph of the reciprocal of lateral pressure versus final displacement is plotted for tests on coated specimens of mixture A. A linear relationship was indicated by the data obtained from these specimens.

Mixture B. Figure 14 graphs the reciprocal of lateral pressure

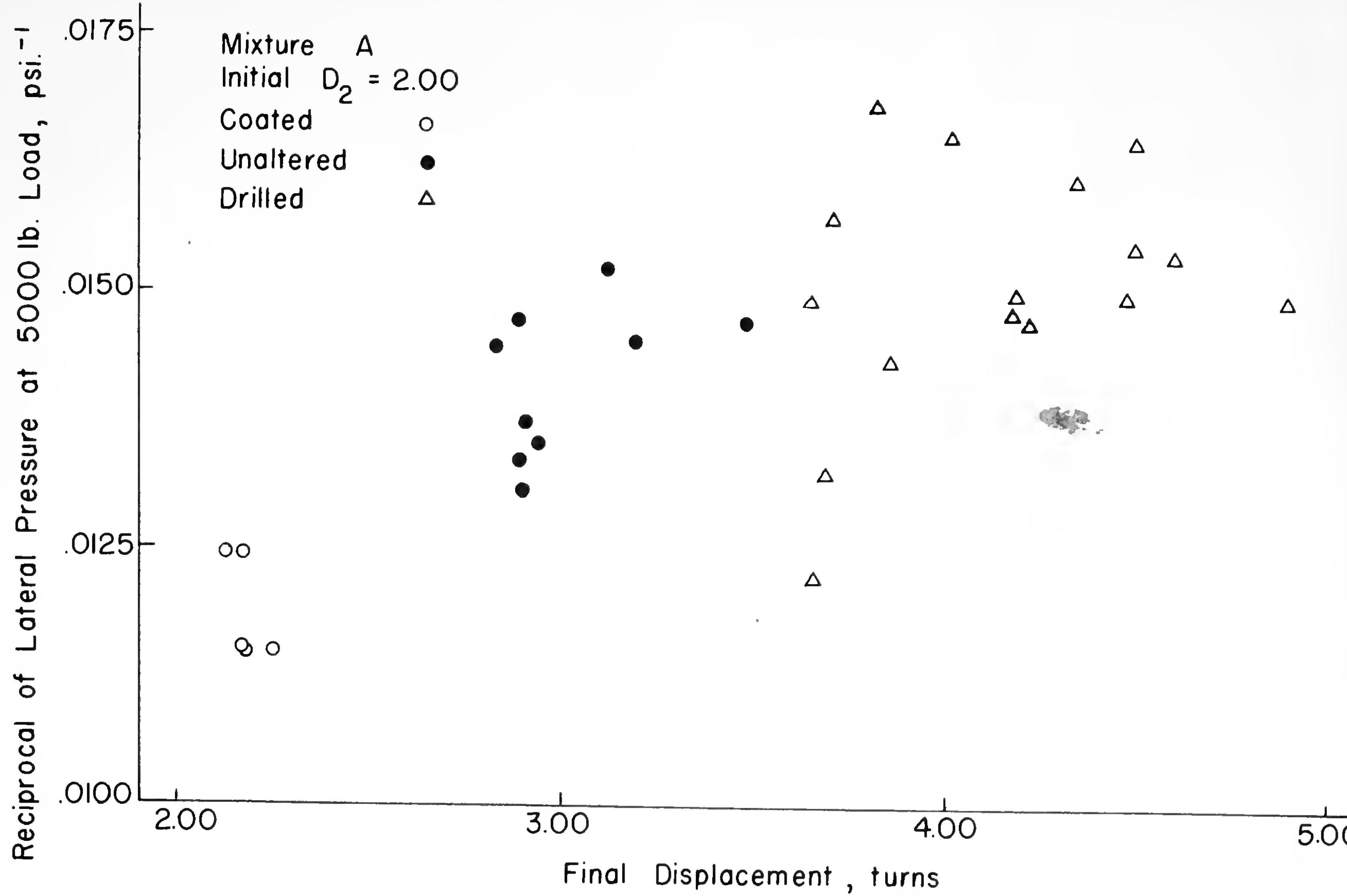

FIG. 12 RECIPROCAL OF LATERAL PRESSURE vs FINAL DISPLACEMENT

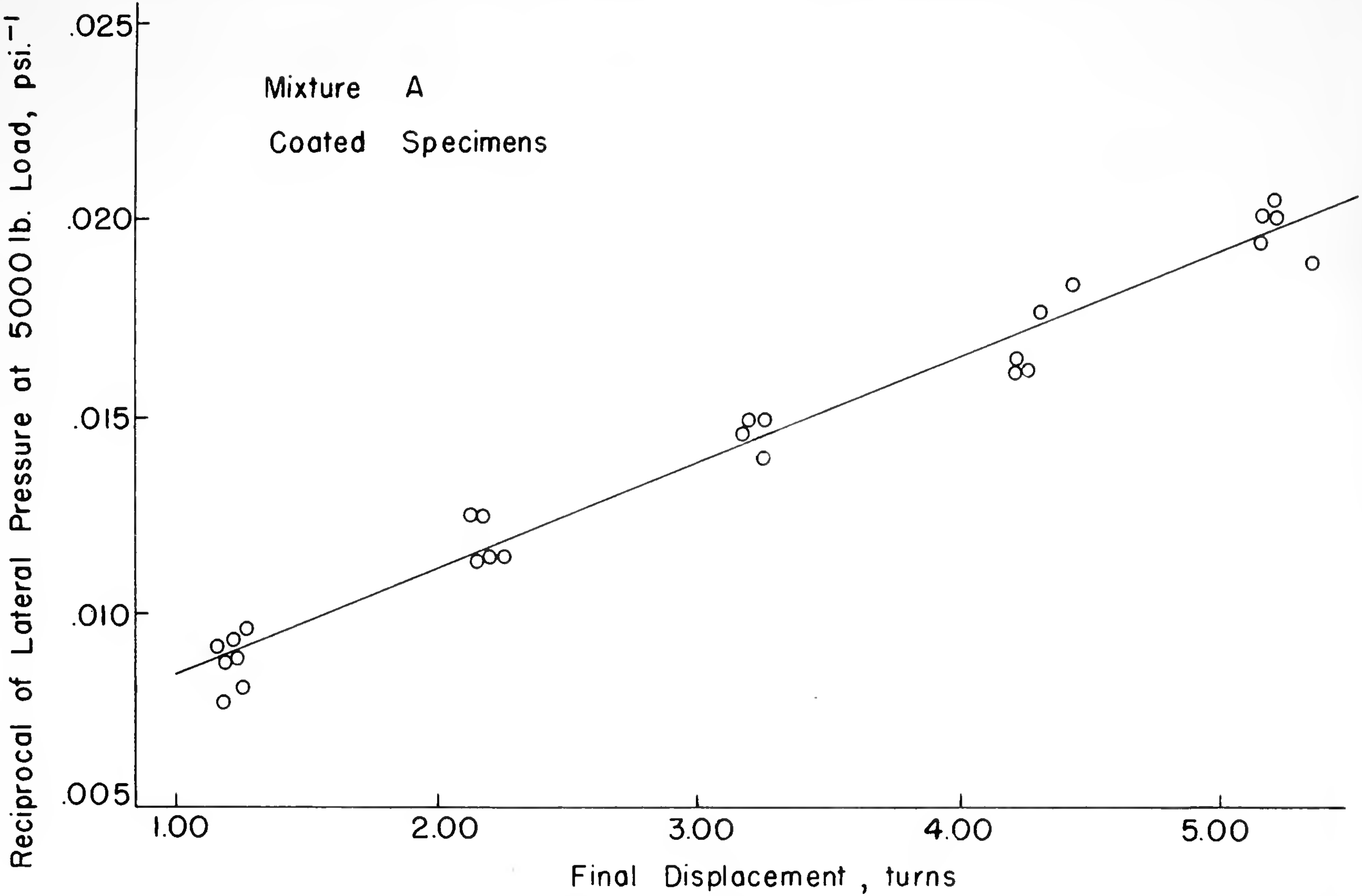

FIG. 13 RECIPROCAL OF LATERAL PRESSURE vs FINAL DISPLACEMENT

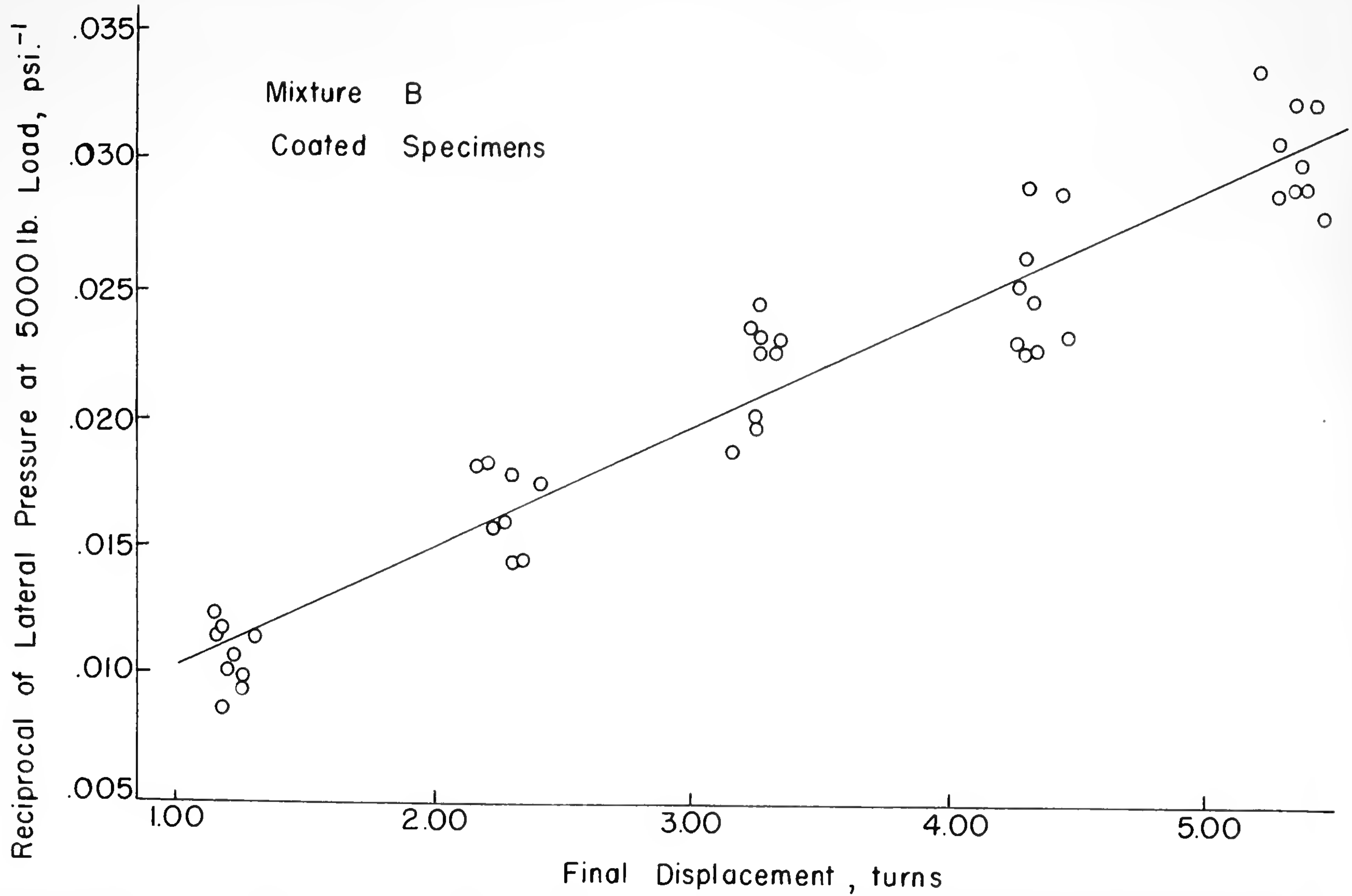

FIG. 14 RECIPROCAL OF LATERAL PRESSURE vs FINAL DISPLACEMENT

against the final displacement measurement for coated specimens of mixture B. Results were somewhat erratic, but the curve appears to be linear.

Mixture C. In Figure 15, the graph of the reciprocal of lateral pressure versus final displacement is plotted for mixture C. A non-linear relationship was obtained from these data rather than the expected straight line.

Comparison of Measured and Theoretical Relationships. The dashed lines shown in Figure 16 represent the relationships between the reciprocal of lateral pressure and values of final displacement which were computed by substituting hypothetical stability values into the Hveem equation. The solid lines, marked A, B, and C, correspond to the curves shown in Figures 13, 14, and 15.

The slopes of the lines corresponding to mixtures A and B are slightly lower than those which represent the stability equation, resulting in smaller values of stability at high values of displacement. Although the curve representing mixture C is not a straight line, it conforms well with the theoretical curve of seventy per cent stability between displacement values of 2.00 and 3.00 turns. Above and below these displacement values, the stability drops off substantially, however.

The deviation from the straight line for mixture C may be due to the extremely low lateral pressure developed by specimens tested at high values of displacement. For initial displacements of 4.00 and 5.00 turns, the average lateral pressures were only 10.3 and 9.2 psi. Each test was started at a 5 psi lateral pressure, and the validity of measurements

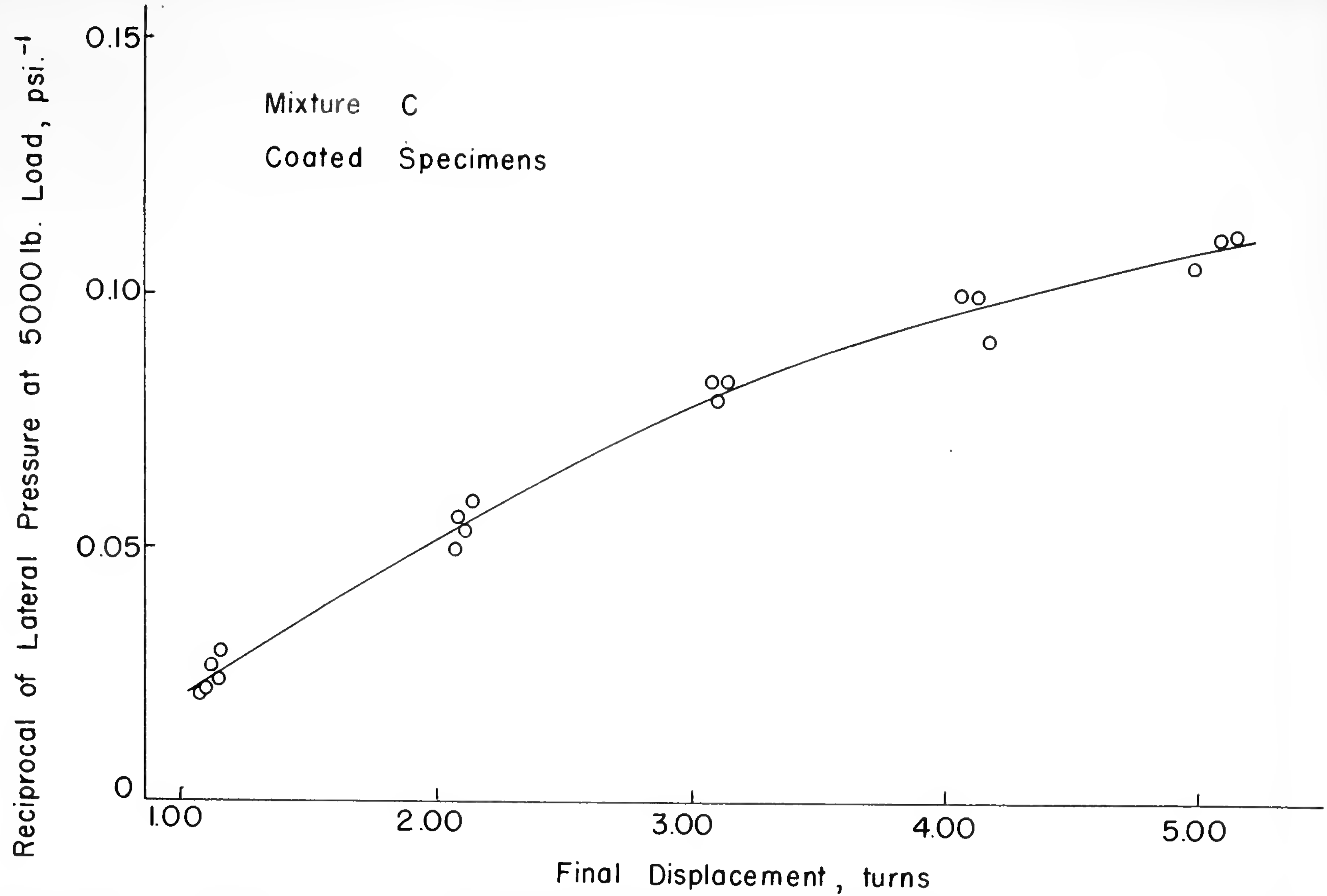

FIG. 15 RECIPROCAL OF LATERAL PRESSURE vs FINAL DISPLACEMENT

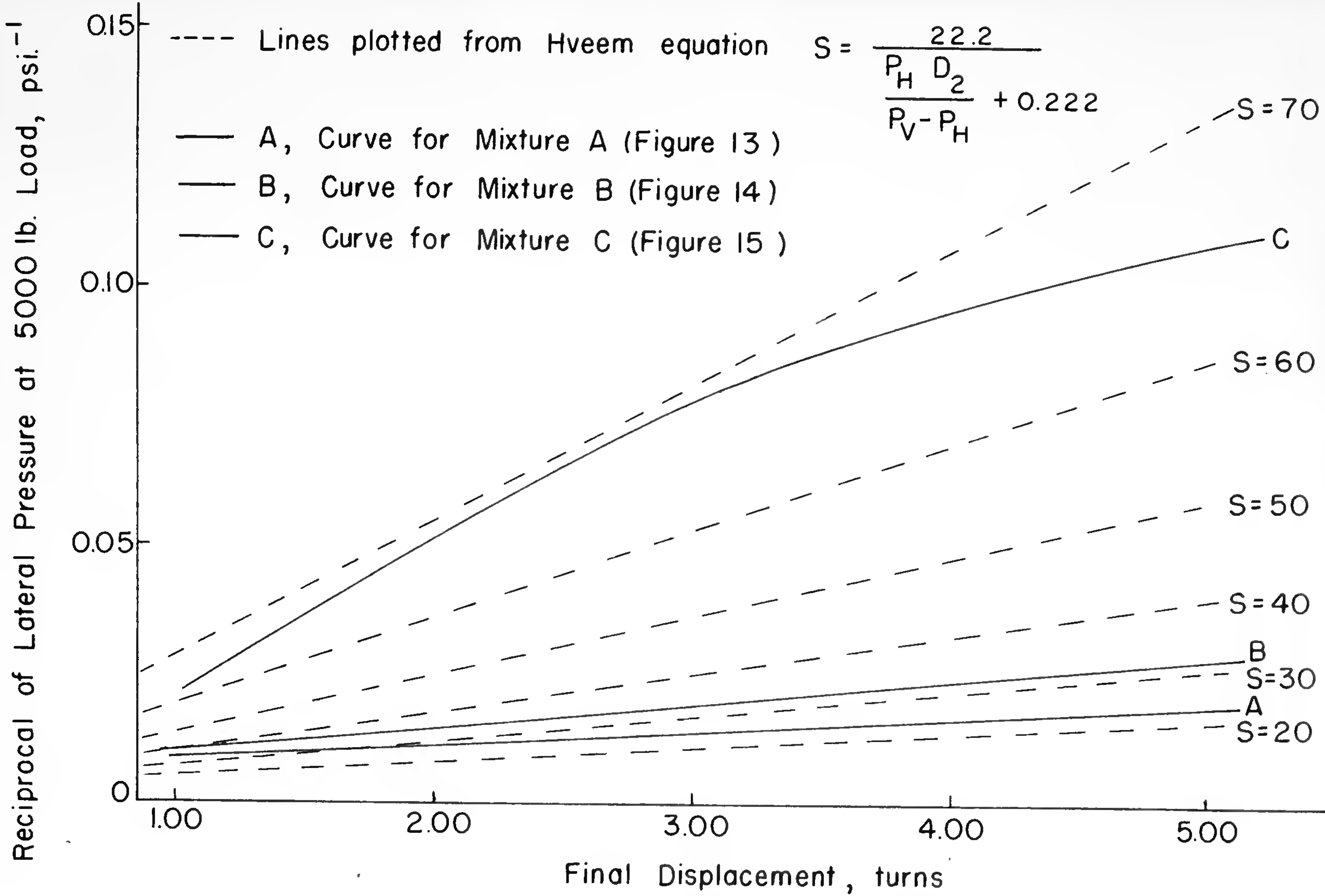

FIG. 16 RECIPROCAL OF LATERAL PRESSURE vs FINAL DISPLACEMENT

at such low pressures is questionable because of the lack of sensitivity of the Stabilometer pressure gauge.

Influence of Vertical Stress and Specimen Deformation on Hveem Stability

Triaxial compression test results for open-graded bituminous mixtures have been reported by Oppenlander (12) and by Oppenlander and Goetz (13, 14). These results showed that, for very open-graded mixtures, the shearing stress developed by the specimen increased as the amount of strain and the confining pressure were increased.

Since the Hveem stability number is based on the amount of strain experienced by a specimen under a 5,000-pound vertical load, the stress-strain characteristics of open-graded mixes, as exhibited by the stabilometer test, are of considerable interest. These characteristics are discussed in this section.

Per Cent Strain versus Deviator Stress

The triaxial compression test results reported by Oppenlander and Goetz were obtained from mixes identical to those designated as mixtures A and D in this study. The stress-strain values for these triaxial tests can be expected to differ from those obtained with the Stabilometer, because the triaxial tests were conducted at constant confining pressures and on taller test specimens. Ideally, the deformations permitted in the Stabilometer test should be compared with those occurring under the actual field condition. Since field data are not available, the triaxial data are used here to obtain a rather general indication of

what quantity of strain should be permitted the Stabilometer test specimen if its resistance is to be fully mobilized.

Mixture A. Figure 17 illustrates the relationship between per cent strain and deviator stress for coated Stabilometer specimens of mixture A tested at initial displacement values of 1.00, 2.00, 3.00, 4.00, and 5.00 turns. It is evident from the shape of the curves that a large portion of the strain occurs during the initial stages of the test when the air in the system is being compressed and the confining pressure is low. As the confining pressure builds up, however, the slope of the curve increases rapidly. Also, higher values of displacement result in greater amounts of deformation and higher deviator stress values for a given vertical load.

The points labeled A and B on Figure 17 represent triaxial test results obtained by Oppenlander and Goetz. Point A shows the strain (1.7 per cent) which occurred at the peak deviator stress (149 psi) for tests conducted at a 30 psi confining pressure. Point B locates the point of maximum deviator stress (326 psi) at a value of 4.2 per cent strain for a confining pressure of 90 psi. A third confining pressure of 150 psi gave a peak deviator stress of 510 psi at a 5.4 per cent strain.

The locations of points A and B conform quite well with the five curves obtained from Stabilometer measurements. The range of strain values for the Stabilometer tests on this well-graded mixture was approximately the same range required to develop the maximum shearing resistances of triaxial specimens tested at confining pressures between 30 and 90 psi.

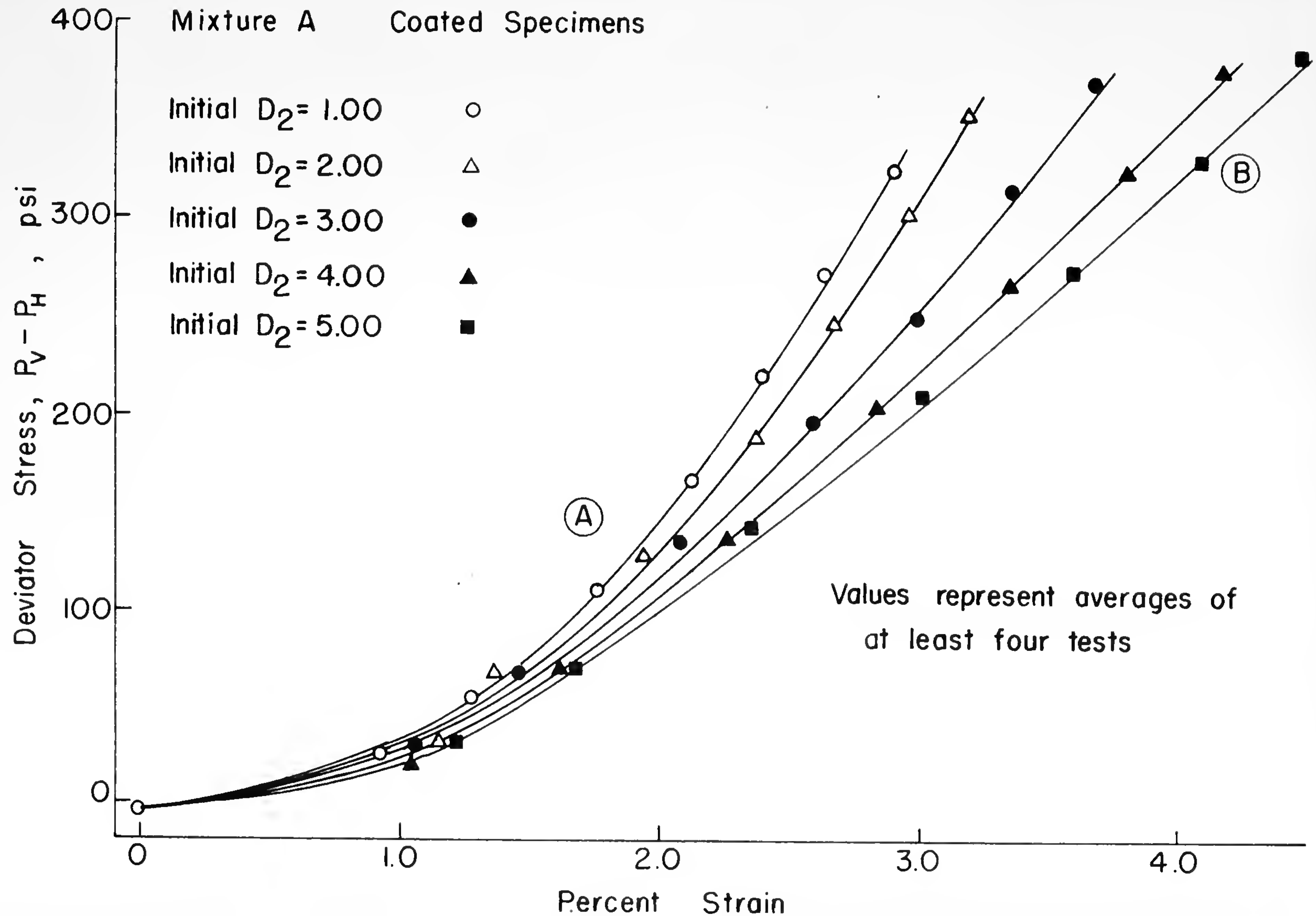

FIG. 17 DEVIATOR STRESS vs PERCENT STRAIN

<u>Mixture D</u>. Figure 18 shows the relationship between per cent strain and deviator stress for Stabilometer tests on the "one-sized" mixture D. One curve represents tests on specimens which had their ends and lateral surfaces coated. The other represents those which had only the lateral surfaces coated. Although initial Stabilometer displacement values were set at 2.00 turns for all tests, it was not possible to fill all the voids on the specimens. Hence, final displacement values were in the range of 3.00 turns.

The maximum strain values for stabilometer tests on mixture D were slightly greater than 5 per cent. For the triaxial tests reported by Oppenlander and Goetz, however, specimens made from this same mixture required more than 15 per cent strain to develop their peak shearing resistances. It is fairly safe to assume, then, that the limited strain conditions in the Stabilometer test do not permit full mobilization of the shear strength of specimens of mixture D. Sufficient information is not available to determine whether the strain afforded this type of specimen by the Stabilometer is compatible with the strain occurring in an actual pavement.

Stabilometer Displacement versus Per cent
Strain at a 5,000-lb. Load

Since the Hveem stability number is computed from the lateral pressure transmitted at a 5,000-pound axial load, it was desired to determine how the Stabilometer displacement measurement affected the per cent strain occurring under this load.

Figure 19 shows the relationship between final displacement and

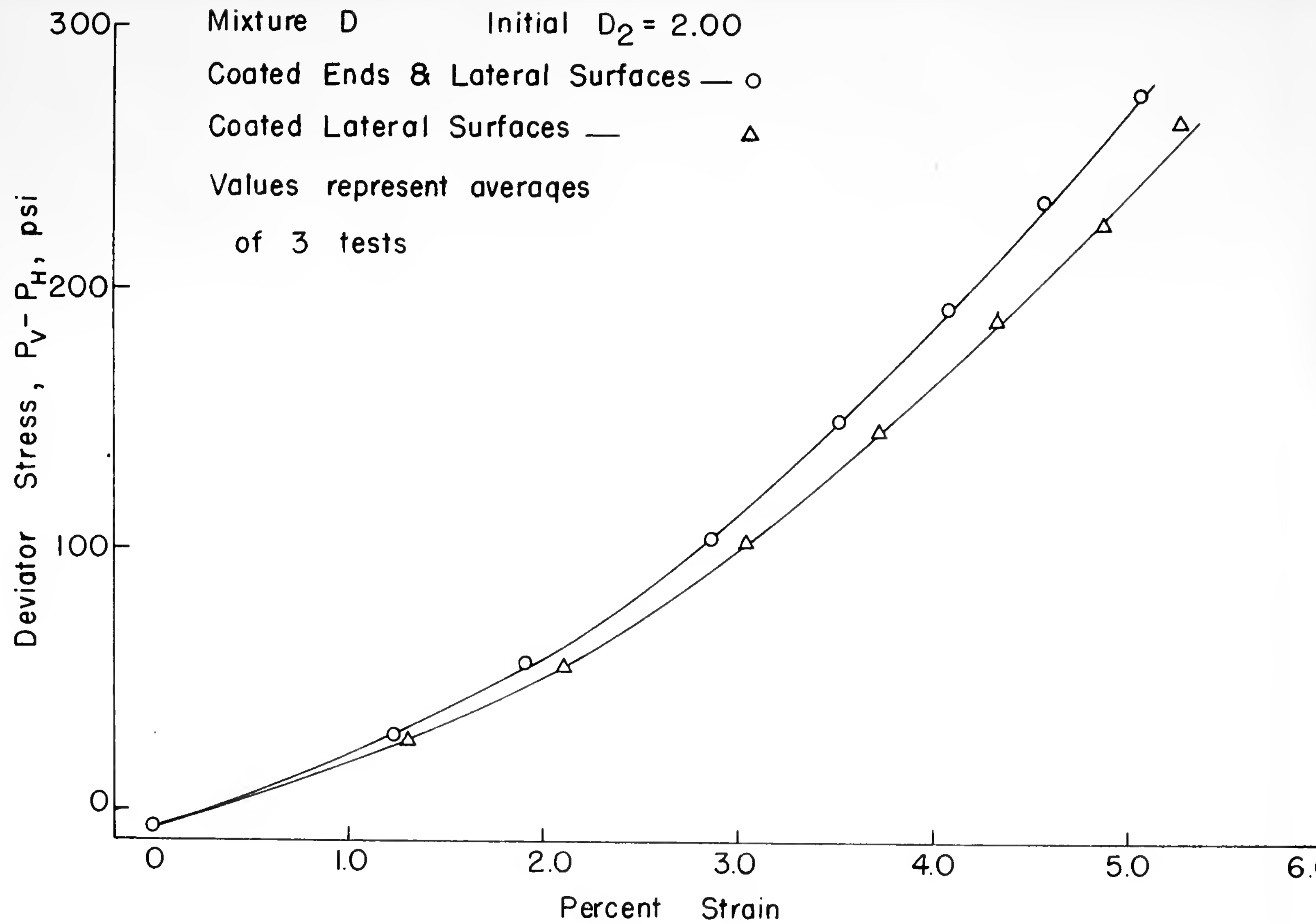

FIG. 18 DEVIATOR STRESS vs PERCENT STRAIN

the per cent strain at a 5,000-pound vertical load for Stabilometer tests on drilled, coated, and unaltered specimens of mixture A. Figure 20 shows this relationship for coated specimens of mixture A. In both cases, increased air in the test system resulted in increased specimen deformation at a load of 5,000 pounds.

Comparison of Results for Specimens with Coated and Unaltered Ends

Surface voids on the ends of Stabilometer test specimens reduce the effective area over which the axial load is applied. This reduced area would appear to give a higher vertical unit stress for a given vertical load. As a result, it is possible that the stability number will be reduced for a specimen having large voids on its ends.

To investigate this aspect of the Stabilometer test, two groups of specimens were fabricated from mixture D. For each group, the lateral surfaces of all specimens were coated with a stiff paste of limestone mineral filler and water. The ends of one group were unaltered, but the second set had the ends coated, as well as the lateral surface.

Appendix C shows the statistical computations used in comparing the mean stability numbers for the two types of specimens tested in this section. The results of this comparison indicated that, at a 5 percent level of significance, Hveem stability numbers were higher for specimens with coated ends than for those with unaltered ends. It should be pointed out, however, that the difference in mean stability numbers for these two types of specimens was relatively small ($\bar{X}_1 - \bar{X}_2 = 1.0$), if compared to the variations in stability values obtained from mixtures A, B, and C.

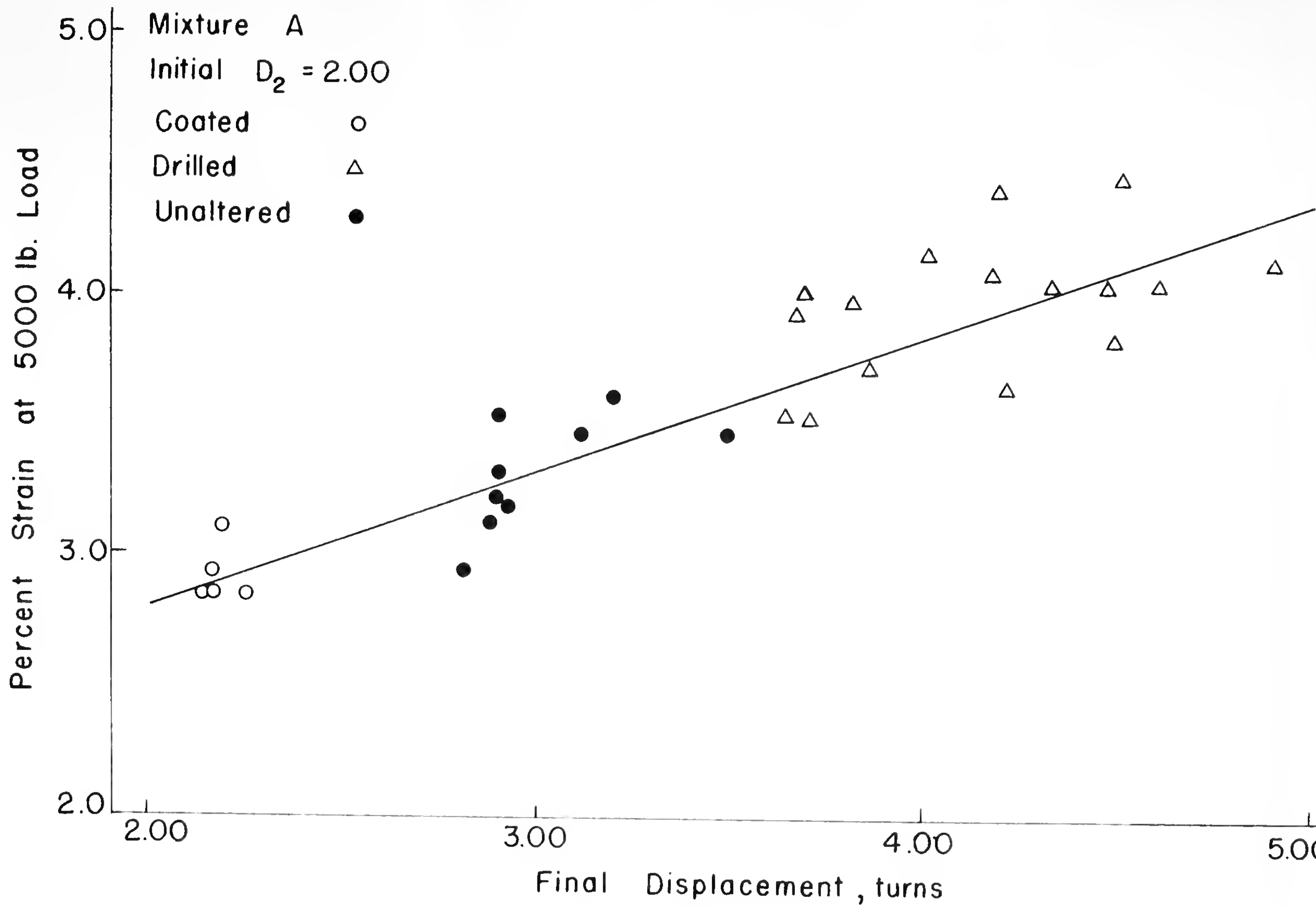

FIG. 19 PERCENT STRAIN vs FINAL DISPLACEMENT

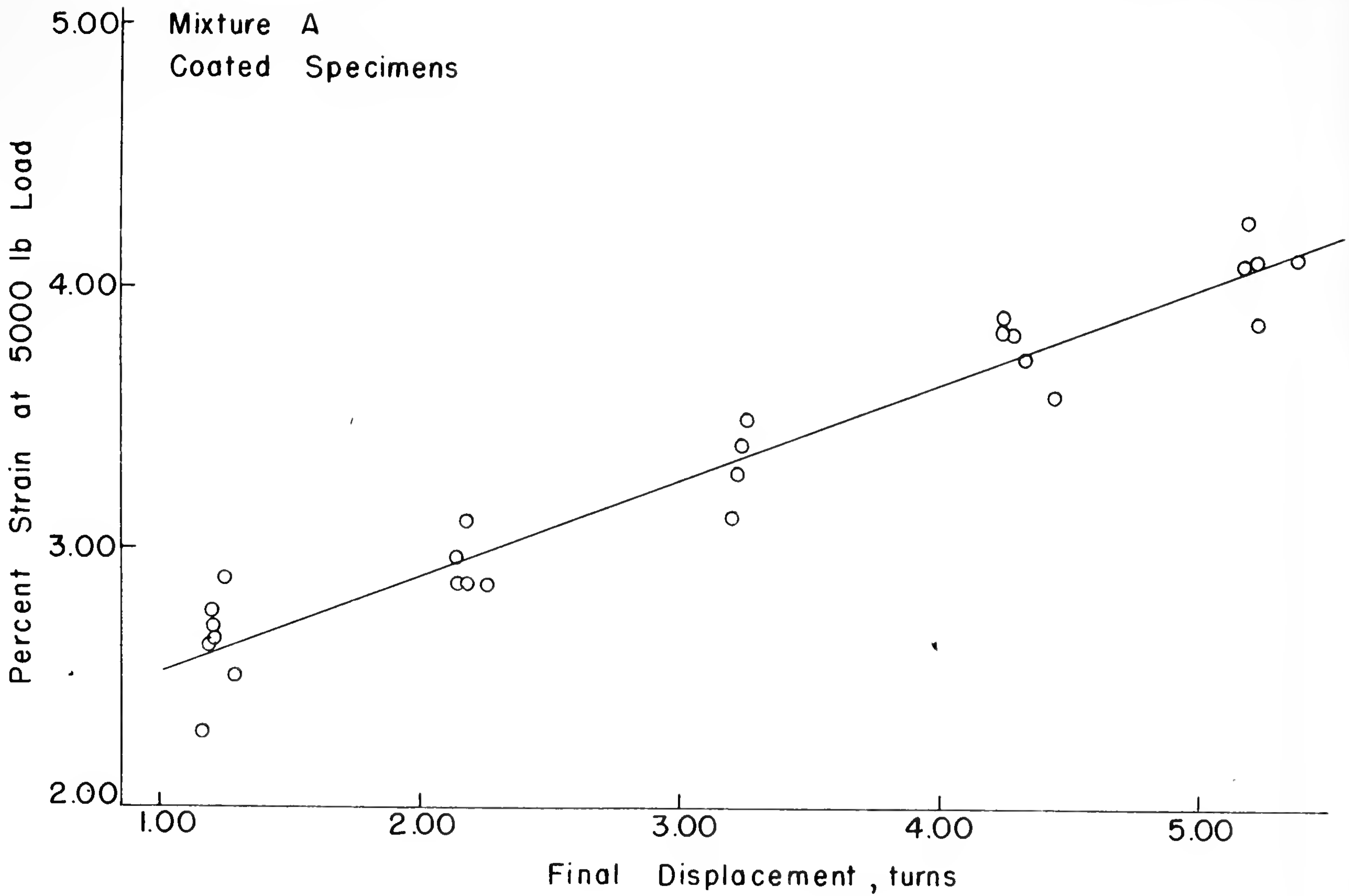

FIG. 20 PERCENT STRAIN vs FINAL DISPLACEMENT

SUMMARY OF RESULTS AND CONCLUSIONS

The conclusions stated here are based solely on test results obtained from the bituminous mixtures incorporated in this study. Before the Hveem Stabilometer test can be applied to the testing of open-graded mixtures with a high degree of confidence, these results should be supplemented with field performance data.

1. As the amount of air in the stabilometer test system was increased, the magnitude of the laterally transmitted pressure was reduced. Stability numbers, as computed from Hveem's equation, remained fairly constant when displacement values did not differ widely (one or less turns of displacement pump) from specimen to specimen. However, when displacement values were increased appreciably, computed Hveem stability numbers were generally reduced.

2. The reproducibility of test results was improved when the Stabilometer was calibrated at displacement values above 2.00 turns and when air voids on the lateral surfaces of specimens were filled prior to testing.

3. The presence of air voids on the ends of test specimens resulted in stability numbers which were not significantly lower but much more erratic than those obtained when these voids were filled. These effects on the stability value for specimens with surface voids on their ends were attributed to the reduced effective area over which the vertical load was applied.

4. During the early stages of a Stabilometer test, air in the system required a relatively large reduction in volume in order to undergo small increases in pressure. As a result, a major portion of the strain experienced by a Stabilometer test specimen was developed at this time. Also, increased quantities of air in the test system, as measured by the displacement value, resulted in greater specimen deformations.

5. Stabilometer tests on the open-graded mixture A gave strain measurements very near to those required to develop the mix's maximum shearing resistance in a rational triaxial compression test of the same mixture conducted at confining pressures similar to those which occur in a Stabilometer test.

6. Strains experienced by Stabilometer test specimens of the "one-sized" mixture D were much lower than those needed to fully mobilize the shearing strength of rational triaxial specimens made from this mixture and exposed to similar confining stresses. Hence, the significance of Stabilometer test results secured from one-sized mixes is questionable and further investigation is desirable.

7. Certain minor modifications in the Stabilometer testing technique appear justified when it is to be applied to the testing of open-graded mixtures.

a. Test specimens capable of yielding final displacement measurements of more than 3.00 turns should have the lateral surface voids filled with a non-cementing mixture such as mineral filler and water. This coating process will improve the reproducibility of results and help to minimize inadequacies in the displacement measurement. Large

voids on the ends of test specimens should be filled to insure a uniform transmission of vertical stress to the specimen's aggregate framework.

b. Tests on specimens having coated lateral surfaces should be conducted at an initial Stabilometer displacement value of 3.00 turns. This modification is made to improve reproducibility of results and to permit more specimen deformation than that which would occur if coated specimens were tested at an initial displacement measurement of 2.00 turns.

SUGGESTIONS FOR FURTHER RESEARCH

Although this study was designed to investigate the applicability of the Hveem Stabilometer Test to open-graded bituminous mixtures, time did not permit an extensive correlation between the performance of these mixes in the field and their stability values as measured by the Stabilometer. Instead, a correlation study of this sort is suggested as a topic for further research. The failure criteria for the Stabilometer test are based on California's highway performance data. This project would give an indication of the stability values needed for satisfactory pavement performance in Indiana.

A second possibility for further study is to investigate the effect of aggregate size on Stabilometer test results. There is good reason to believe that specimens containing aggregate particles greater than 1/2 inch in size will not give representative stability values because of the relatively small dimensions of the specimen.

The mechanical kneading compactor, which is used to mold Stabilometer specimens, provides another topic for additional research. Using the current compaction procedure, this machine will produce excessive aggregate fracture in very open-graded mixtures, and for this reason does not simulate the true field compaction of such a mix. By varying the pressure and number of load applications of the tamping foot, the kneading compactor could conceivably be used to fabricate specimens from a wide range of bituminous mixes.

Another research subject which would be of future value to the field of bituminous mix design is a correlation between the Hveem stability number and the parameters ϕ and C as measured by the rational triaxial compression test. This study would involve the testing of a variety of mixes, both open and dense, and could help to clear up a number of the problems which have prevented the formulation of a purely rational method of mix design.

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APPENDIX

APPENDIX A

APPARATUS AND DETAILED PROCEDURES

APPENDIX A

APPARATUS AND DETAILED PROCEDURES

The laboratory apparatus and detailed procedures used in this investigation are described under the following headings:

1. Preparation of Aggregate
2. Preparation of Test Specimens
3. Hveem Stabilometer Tests

Preparation of Aggregate

The apparatus used in the preparation of the mineral aggregate was as follows:

1. Gilson mechanical sieving machine.
2. Tyler "Ro-Tap" testing sieve shaker.
3. U. S. Standard Sieves, sizes $\frac{3}{4}$ in., $1\frac{1}{2}$ in., 3/8 in., nos. 4, 8, 16, 30, 50, 100, and 200.
4. Torsion balance, capacity 4.5 kg., accuracy $\frac{1}{4}$ gram.

In order to provide a close control over the aggregate gradation for each test specimen, the aggregate obtained from the commercial plants was sieved into the needed sieve fractions. A Gilson mechanical sieving machine was used to separate the coarse aggregate into the fractions of $\frac{3}{4}$ in. to $\frac{1}{2}$ in., $\frac{1}{2}$ in. to 3/8 in., and 3/8 in. to #4. A Taylor "Ro-Tap" testing sieve shaker was used to divide the fine aggregate into fractions of #4 to #8, #8 to #16, #16 to #30, #30 to #50,

#50 to #100, #100 to #200, and passing #200. Sieved aggregate fractions were stored in covered containers until needed for mixing operations. At that time, the individual aggregate sizes were recombined to give the desired aggregate gradations. To form compacted test specimens of the desired $2\frac{1}{2}$-inch height, the respective aggregate batch weights for gradings A, B, C, and D were 1092 grams, 1073 grams, 1121 grams, and 900 grams. These weighings were made on the torsion balance just prior to the preparation of the test specimen.

Preparation of Test Specimens

The following list includes all apparatus needed to prepare test specimens in this investigation:

1. Peerless gas oven with temperature regulator.
2. Ohaus beam balance, capacity 20 kg, accuracy 1.0 grams.
3. Modified Hobart mixer with steel paddle and flat bottomed brass bowl.
4. Steel rod, 5/8-inch diameter, 17-inch length.
5. Steel compaction molds, 4-inch diameter, 5-inch height.
6. Riehle testing machine (50,000 pound capacity) with variable speed drive.
7. Triaxial Institute Mechanical Kneading Compactor, equipped with 4-inch diameter molds, mold holder, and insulated feeder trough.
8. Blackhawk hydraulic jack (50 ton capacity).
9. Steel compaction frame.
10. Cleveland pneumatic vibrator.
11. Hobart Brothers air compressor.
12. Extrusion collar (collar of Marshall mold).
13. Split mold, 4-inch diameter.

14. Delta drill press and 3/8-inch carbide-tipped steel drill.

15. Miscellaneous equipment. Pans, beakers, metal spoons, spatulas, thermometers, stop watch, heat-resistant gloves, paper discs, steel pistons, feeder trough blade, sandpaper, etc.

Because of the wide variations in compaction techniques, the procedure for molding Stabilometer test specimens will be discussed according to mixture type.

Mixtures A and B

1. For each specimen to be molded, approximately 80 grams of asphalt cement was put into a 400 ml metal beaker.

2. Metal pans containing the batched aggregate mixtures were placed on the top shelf of the oven, the temperature of which was maintained at $300 \pm 10^\circ$F.

3. When the mineral aggregate reached the $300 \pm 10^\circ$F temperature, one beaker of asphalt was placed on the top shelf of the oven. At the same time, the mixing bowl, mixing paddle, steel rod, spoon, spatula, mold, and upper and lower pistons were placed on the second shelf.

4. When the asphalt reached a temperature of $275 \pm 5^\circ$F, the mineral aggregate was placed into the mixing bowl, and the bowl and aggregate were tared on the beam balance. The required weight of asphalt was then added to the beam, and the hot asphalt was poured into the bowl until the beam became balanced.

5. The mixing paddle was removed from the oven and the paddle and bowl were connected to the mixer. The asphalt and aggregate were then mixed at the slow mixer speed for a period of two minutes.

6. While the mixing was being accomplished, the mold, spatula,

spoon, pistons, and steel rod were removed from the oven. The lower piston was inserted into the mold where it was held in place with a steel pin. A 4-inch diameter paper disc was placed in the bottom of the mold to prevent adhesion of the mixture to the metal piston.

7. At the end of the mixing period, the material was spooned from the bowl into the mold in two equal layers. Each layer was rodded 40 times with the steel rod.

8. A paper disc was placed on top of the mixture and the upper piston was inserted into the mold.

9. The mold was placed in the compression machine and the steel pin was removed from the mold to permit vertical movement of the lower piston.

10. A vertical load was applied to the mixture at a rate of 0.165 inches per minute. When the load reached 27,500 pounds, the clutch was maneuvered so as to keep the load constant for one minute. At the end of this time, the load was removed and the specimen allowed to cool to room temperature.

11. To remove the cooled specimen from the mold, the specimen was extruded into the upper half of a Marshall compaction mold. This was done in the compression machine at a rate of 0.84 inches per minute.

12. At this point the treatment of the test specimen was varied, depending on whether it was fabricated from mixture A or mixture B.

a. The lateral surface of a specimen made from mix A was either left unaltered, was drilled to form a number of shallow voids, or was coated with a stiff mixture of portland cement, plaster of paris and water. To provide the specimen with a smooth lateral surface,

the mixture was allowed to harden, and the excess material was removed with sandpaper.

b. All specimens made from mixture B were coated with the cement-plaster-water mixture and then sandpapered.

Mixture C

1. The electrical power switches of the kneading compactor were engaged and the compaction foot heater was started with the powerstat set at 80.

2. Asphalt was placed in metal beakers as was done for mixtures A and B, and the aggregate was placed on the top shelf of the oven with the temperature controlled at $300 \pm 10°F$.

3. When the aggregate's temperature reached $300 \pm 10°F$, the asphalt cement was placed on the top shelf of the oven. The mixing bowl, mixing paddle, spoon, spatula, and steel rod were placed on the second shelf.

4. When the temperature of the asphalt became $275 \pm 5°F$, the aggregate was added to the mixing bowl, and the bowl plus aggregate were tared on the beam balance. The desired weight of asphalt was then added to the bowl.

5. The asphalt and aggregate were mixed for two minutes at the slow mixing speed. During this time the spoon, spatula, and steel rod were removed from the oven and the mold was fitted into the special mold holder. A 1/4-inch shim was placed between the bottom of the mold and the base, and the set screw was tightened against the side of the mold. A 4-inch diameter paper disc was placed in the bottom of the mold.

6. After mixing operations were completed, the mix was not subjected to the fifteen-hour curing time specified by California. Instead, the mixture was spooned directly into the mold and rodded 40 times. The mold and holder were then attached to the turntable of the compactor.

7. The compactor was started, and 20 tamps were applied to the mixture at a 250 psi pressure.

8. When the 20 tamps at 250 psi had been applied, the pressure was increased to 500 psi and the timer set for five minutes (150 tamps). The metal shim under the mold was removed, the set screw loosened, and a paper disc placed over the specimen.

9. When the machine stopped automatically after 150 tamps at 500 psi, the mold was removed from the holder, and the upper and lower pistons inserted in the mold.

10. The mixture was then subjected to a 12,600 pound "leveling-off" load at a rate of 0.25 inches per minute. When the 12,600 pound load was obtained, the testing machine was immediately shut off, and the load removed.

11. The specimen was cooled to room temperature and removed from the mold by extrusion into the upper portion of a Marshall mold.

12. After extruding the specimen, its lateral surface was coated with a mixture of portland cement, plaster of paris, and water. When dry, the surface was sandpapered.

Mixture D

1. Approximately 60 grams of asphalt cement were placed in each of several 400 ml metal beakers, one for each specimen to be made.

2. The batched aggregate mixes were placed on the top shelf of the gas oven, the temperature of which was 300 $\pm$ 10°F.

3. When the aggregate reached 300 $\pm$ 10°F, the asphalt was placed on the top shelf of the oven. The mixing bowl, mixing paddle, spoon, spatula, feeder trough, and feeder trough blade were put on the second shelf.

4. When the asphalt reached a temperature of 275 $\pm$ 5°F, the aggregate was put in the mixing bowl and tared on the beam balance. The necessary quantity of asphalt was then poured into the bowl.

5. The bowl and paddle were attached to the mixer and mixed for a period of two minutes.

6. At the end of the mixing period, the mix was transferred from the bowl to the insulated trough and placed back on the third shelf of the oven. The purpose of the trough, of course, was to reduce the excessive segregation which could occur in a one-sized mix of this type.

7. While the mixture and trough were in the oven, the lower piston was inserted into the mold and a paper disc was placed above the piston.

8. When the mix and trough reached a temperature of 230 $\pm$ 5°F, the mixture was transferred from the trough into the mold in two equal layers. Each layer was rodded 40 times.

9. A paper disc was placed on top of the rodded mix and the upper piston was added. The mold was then placed in the compaction frame, with the vibrator resting above the upper piston.

10. A vertical load of 600 pound was applied with the hydraulic

jack and the vibrator was started. With the vibrator operating continuously under an 80 psi pressure, the load was held at 600 pounds for 30 seconds and then increased to 12,600 pounds at a rate of 200 pounds per second. The 12,600 pound load was held constant for one minute, after which the vibrator was stopped and the load released.

11. The specimen was left in the mold for 24 hours before being extruded into a Marshall mold. After the extrusion process, the specimen was laid on its side in one half of a 4-inch diameter split mold. Steel pistons were also placed in the mold at each end of the specimen to prevent the compacted mixture from slumping.

12. Approximately two hours before testing, the specimen was removed from the split mold and coated with a stiff mixture of limestone mineral filler and water. For one group of specimens, the entire surface of the specimen was coated. For a second group, only the lateral surface was coated.

Hveem Stabilometer Tests

The equipment used to conduct Hveem Stabilometer tests in this investigation is outlined below:

1. Hveem Stabilometer test cell, follower-piston, and dummy metal specimen.
2. Riehle testing machine (50,000 pound capacity) with variable speed drive.
3. 10,000 pound proving ring.
4. Dial indicator, 0.001 inch scale divisions, 2-inch movement.
5. Dial indicator support bracket.
6. Thermometer.
7. 12-inch scale.

The method of conducting a Hveem Stabilometer test as used in this study can be described as follows:

1. Prior to the test, the height of the specimen was obtained with a dial indicator fastened to a support bracket. The height of the specimen was determined by first referring the indicator dial reading to a known height and then taking a dial reading on the actual test specimen.

2. For tests in which deformation measurements were recorded, the 10,000 pound proving ring was bolted to the upper platen of the testing machine and the deflection indicator dial was bracketed to the machine to measure the distance travelled by the upper platen during the test.

3. The adjustable Stabilometer base was set so as to provide an effective contact height of 2.4 inches between the rubber diaphragm and the specimen.

4. The Stabilometer was calibrated with the dummy metal specimen and the desired quantity of air was admitted to the oil chamber through the needle valve. Because this quantity of air was varied for several tests, the initial displacement measurement ranged from 1.00 to 5.00 turns.

5. The test specimen was placed inside the Stabilometer cell which, in turn, was positioned in the testing machine.

6. The testing machine was started and the speed set at 0.05 inches per minute. The Stabilometer displacement pump was turned inward to increase the lateral pressure to 5 psi. prior to the start of the test.

7. Load was measured with a proving ring or by the weigh beam of the test machine.

a. When deformation measurements were being taken, the upper platen of the testing machine was lowered until a small seating load was recorded on the proving ring indicator dial. The deflection indicator dial was then set to read zero.

b. For tests involving no deformation measurements, vertical load readings were taken with the calibrated beam of the testing machine. This beam was balanced to read zero at the start of each test with the Stabilometer resting on the lower platen.

8. The vertical load was applied and carried to 6000 pounds.

a. When strain values were desired, lateral pressure and deformation dial readings were recorded at incremental vertical loads of 250 pounds.

b. When deformations were not recorded, lateral pressure readings were taken at vertical loads of 500, 1000, 2000, 3000, 4000, 5000, and 6000 pounds.

9. At the instant the 6000 pound load was reached, the testing machine was turned off and the load reduced to 1000 pounds. The lateral pressure was backed off with the displacement pump to a reading slightly below 5 psi, and then returned to the 5 psi pressure.

10. The final displacement measurement was recorded as the number of turns of the displacement pump needed to increase the lateral pressure reading from 5 psi to 100 psi.

11. The 1000 pound load was then removed, the room temperature recorded, and the specimen taken out of the Stabilometer.

APPENDIX B

DATA

APPENDIX B

DATA

Stabilometer test results for specimens of mixtures A, B, C and D are tabulated in this section. Properties listed here include the following:

1. Per cent strain, ϵ, at vertical loads of 500, 1000, 2000, 3000, 4000, 5000, and 6000 pounds.
2. Lateral pressure, P_h, in pounds per square inch, at vertical loads of 500, 1000, 2000, 3000, 4000, 5000, and 6000 pounds.
3. Deviator stress, $P_v - P_h$, in pounds per square inch, at vertical loads of 500, 1000, 2000, 3000, 4000, 5000, and 6000 pounds.
4. Final displacement measurement, D_2, in the unit of turns.
5. Hveem stability number, S, as calculated from the equation

$$S = \frac{22.2}{\dfrac{P_h D_2}{P_v - P_h} + 0.222} \quad .$$

TABLE 5

Stabilometer Test Results | Mixture A

Initial Displacement = 2.00 | Unaltered Specimens

Test No.	Property	Strain, Lateral Pressure at Incremental Loads 500	1000	2000	3000	4000	5000	6000	Final Displ.	Hveem Stability
1	ϵ	1.21	1.58	2.23	2.63	2.99	3.32	3.60	2.90	25.6
	P_h	8.0	12.5	23.0	37.5	54.0	73.0	94.5		
2	ϵ	1.05	1.33	1.89	2.30	2.62	2.94	3.23	2.81	27.3
	P_h	8.0	12.0	21.5	35.0	51.0	69.5	91.0		
3	ϵ	1.41	1.69	2.25	2.77	3.17	3.53	3.86	2.90	24.3
	P_h	8.0	12.0	22.5	37.5	56.0	77.0	101.0		
4	ϵ	1.01	1.34	1.95	2.43	2.80	3.12	3.40	2.88	27.3
	P_h	7.0	10.0	20.0	33.5	49.5	68.0	88.5		
5	ϵ	1.01	1.41	2.06	2.54	2.87	3.19	3.47	2.93	25.1
	P_h	8.5	12.5	22.5	37.0	53.5	74.0	95.5		
6	ϵ	0.98	1.39	2.04	2.53	2.85	3.22	3.50	2.89	25.0
	P_h	8.5	13.5	25.0	40.0	56.0	75.0	95.0		
7	ϵ	1.20	1.60	2.21	2.77	3.25	3.61	3.93	3.19	25.0
	P_h	8.5	12.5	21.5	34.5	50.0	69.0	89.0		
8	ϵ	1.21	1.62	2.22	2.71	3.07	3.47	3.75	3.11	25.0
	P_h	8.5	12.0	20.5	33.0	47.5	66.0	85.5		
9	ϵ	1.04	1.52	2.11	2.67	3.11	3.47	3.83	3.48	23.7
	P_h	8.5	12.5	21.5	34.5	49.0	68.0	89.5		

ϵ = Per cent strain, P_h = Lateral pressure.

TABLE 6

Stabilometer Test Results — Mixture A

Initial Displacement = 2.00 — Drilled Specimens

Test No.	Property	Strain, Lateral Pressure at Incremental Loads 500	1000	2000	3000	4000	5000	6000	Final Displ.	Hveem Stability
1	ϵ	1.21	1.74	2.46	3.03	3.47	3.92	4.28	3.67	19.0
	Ph	8.5	12.5	23.0	39.0	58.5	82.0	106.5		
2	ϵ	1.38	1.91	2.59	3.16	3.57	4.01	4.38	3.69	21.8
	Ph	8.5	12.5	20.5	34.0	51.0	71.0	93.5		
3	ϵ	1.32	1.96	2.73	3.41	3.97	4.45	4.85	4.49	20.3
	Ph	8.5	12.0	19.0	30.5	45.5	65.0	87.0		
4	ϵ	1.07	1.59	2.43	3.10	3.66	4.09	4.49	4.16	20.8
	Ph	8.0	11.0	18.5	30.5	47.0	67.5	89.0		
5	ϵ	1.19	1.62	2.30	2.93	3.57	4.04	4.48	4.32	21.9
	Ph	7.5	10.0	16.0	25.0	40.5	62.0	85.0		
6	ϵ	1.28	1.80	1.97	3.00	3.52	3.99	4.39	3.80	25.0
	Ph	8.0	10.5	16.5	26.0	40.0	59.5	81.0		
7	ϵ	1.16	1.68	2.31	2.87	3.31	3.71	4.07	3.84	21.4
	Ph	8.5	12.5	20.5	33.5	49.5	70.0	92.0		
8	ϵ	1.75	1.59	2.23	2.75	3.14	3.54	3.90	3.64	23.3
	Ph	8.5	12.5	20.0	32.0	47.5	67.0	88.5		
9	ϵ	0.96	1.44	2.04	2.60	3.08	3.52	3.88	3.72	24.1
	Ph	8.0	11.0	18.0	29.0	44.0	63.5	84.0		

(continued)

(continued) TABLE 6

Stabilometer Test Results — Mixture A

Initial Displacement = 2.00 — Drilled Specimens

Test No.	Property	Strain, Lateral Pressure at Incremental Loads 500	1000	2000	3000	4000	5000	6000	Final Displ.	Hveem Stability
10	ϵ	1.28	1.84	2.68	3.40	3.96	4.40	4.80	4.18	20.9
	Ph	8.5	12.0	19.5	27.5	47.0	67.0	89.5		
11	ϵ	1.01	1.53	2.34	3.02	3.59	4.07	4.47	4.00	24.9
	Ph	7.5	10.0	16.5	25.5	39.0	57.5	77.5		
12	ϵ	1.03	1.47	2.18	2.78	3.25	3.65	4.01	4.21	20.4
	Ph	8.0	10.5	18.5	30.5	47.5	68.0	91.0		
13	ϵ	1.20	1.80	2.49	3.17	3.65	4.05	4.41	4.59	19.9
	Ph	8.0	11.0	18.0	30.0	45.5	65.5	87.0		
14	ϵ	1.20	1.73	2.45	3.13	3.69	4.13	4.49	4.88	18.5
	Ph	8.0	11.0	18.0	29.0	46.0	67.0	90.0		
15	ϵ	1.11	1.62	2.38	3.01	3.56	4.04	4.48	4.46	19.8
	Ph	7.5	10.5	18.0	30.0	46.0	67.0	91.0		
16	ϵ	1.15	1.59	2.30	2.89	3.41	3.85	4.28	4.48	21.7
	Ph	7.5	9.5	15.5	25.5	41.0	61.0	83.0		

ϵ = Per cent strain, P_h = Lateral pressure.

TABLE 7

Stabilometer Test Results — Mixture A

Initial Displacement = 1.00 — Coated Specimen

Test No.	Property	Strain, Lateral Pressure, Deviator Stress at Incremental Loads							Final Displ.	Hveem Stability
		500	1000	2000	3000	4000	5000	6000		
1	ϵ	0.85	1.17	1.61	1.93	2.22	2.50	2.74	1.27	32.8
	Ph	12.0	21.0	40.0	61.0	83.0	105.5	129.0		
	Pv - Ph	27.4	57.6	116.5	173.0	228.0	282.4	335.4		
2	ϵ	0.76	1.08	1.52	1.84	2.08	2.28	2.52	1.16	33.5
	Ph	13.0	22.5	44.5	66.0	87.5	110.0	133.0		
	Pv-- Ph	26.5	56.2	112.2	168.2	224.0	278.8	332.5		
2	ϵ	1.01	1.41	1.89	2.26	2.50	2.74	3.02	1.19	32.7
	Ph	11.5	21.5	43.0	65.5	87.0	111.0	136.0		
	Pv - Ph	27.9	56.9	113.1	167.8	223.3	276.0	327.0		
4	ϵ	1.00	1.37	1.81	2.17	2.41	2.65	2.85	1.21	32.9
	Ph	11.5	21.5	42.0	64.0	86.0	109.0	135.0		
	Pv - Ph	27.9	57	114.2	169.5	224.6	278.3	328.7		
5	ϵ	0.89	1.25	1.73	2.09	2.38	2.62	2.86	1.18	28.3
	Ph	13.0	24.5	51.0	77.0	102.5	129.0	154.5		
	Pv - Ph	26.4	54.1	105.4	156.6	208.1	258.3	309.2		
6	ϵ	0.99	1.38	1.93	2.32	2.64	2.86	3.15	1.25	28.6
	Ph	14.0	26.0	51.0	75.0	99.0	123.0	148.0		
	Pv - Ph	25.4	52.4	105.0	158.1	210.8	263.4	314.2		

continued

(continued)

TABLE 7

Stabilometer Test Results — Mixture A

Initial Displacement = 1.00 — Coated Specimens

Test No.	Property	Strain, Lateral Pressure, Deviator Stress at Incremental Loads 500	1000	2000	3000	4000	5000	6000	Final Displ.	Hveem Stability
7	ϵ	0.98	1.39	1.84	2.16	2.45	2.69	2.94	1.18	32.6
	Ph	11.5	20.5	42.5	66.0	88.0	112.0	134.0		
	Pv - Ph	27.9	57.9	113.6	167.5	222.3	275.0	326.3		
Avg.	ϵ	0.93	1.29	1.76	2.11	2.38	2.62	2.87	1.21	31.6
	Ph	12.36	22.5	44.8	51.5	90.4	114.2	163.1		
	Pv - Ph	27.1	56.0	111.4	165.8	220.2	273.2	324.8		

ϵ = Per cent strain, Ph = Lateral pressure, $P_v - P_h$ = Deviator stress

TABLE 8

Stabilometer Test Results | Mixture A

Initial Displacement = 2.00 | Coated Specimens

Test No.	Property	Strain, Lateral Pressure, Deviator Stress at Incremental Loads							Final Displ.	Hveem Stability
		500	1000	2000	3000	4000	5000	6000		
1	ϵ	1.12	1.32	1.85	2.29	2.57	2.85	3.09	2.13	29.3
	Ph	7.5	11.5	23.0	40.0	59.0	80.5	104.0		
	Pv - Ph	31.8	67.0	133.1	193.3	251.1	305.9	358.6		
2	ϵ	1.20	1.44	1.97	2.37	2.69	2.93	3.17	2.16	29.0
	Ph	8.5	13.0	25.0	41.5	60.0	80.5	104.0		
	Pv - Ph	30.8	65.4	131.0	191.4	249.6	305.6	358.3		
3	ϵ	0.93	1.37	2.06	2.50	2.82	3.10	3.35	2.18	26.5
	Ph	9.5	16.0	30.5	48.0	68.0	88.0	111.0		
	Pv - Ph	29.9	62.5	125.4	184.7	241.4	297.5	350.2		
4	ϵ	1.05	1.41	1.93	2.33	2.61	2.85	3.09	2.17	26.6
	Ph	8.0	13.5	27.5	45.0	65.0	87.0	111.0		
	Pv - Ph	31.4	64.9	128.5	188.1	244.8	299.4	351.6		
5	ϵ	0.97	1.29	1.85	2.30	2.62	2.86	31.4	2.25	26.1
	Ph	8.5	14.0	28.0	46.0	66.0	87.5	111.0		
	Pv - Ph	30.9	74.2	128.1	187.1	243.8	298.9	351.6		
Avg.	ϵ	1.05	1.37	1.93	2.36	2.66	2.92	3.17	2.18	27.5
	Ph	8.4	13.6	26.8	44.1	63.6	84.7	108.2		
	Pv - Ph	31.0	66.8	129.2	188.9	246.1	301.5	354.1		

ϵ = Per Cent Strain, P_h = Lateral Pressure, $P_v - P_h$ = Deviator Stress

TABLE 9

Stabilometer Test Results

Mixture A

Initial Displacement = 3.00

Coated Specimens

Test No.	Property	Strain, Lateral Pressure, Deviator Stress at Incremental Loads 500	1000	2000	3000	4000	5000	6000	Final Displ.	Hveem Stability
1	ϵ	1.05	1.50	2.06	2.55	2.95	3.28	3.60	3.21	26.3
	Ph	8.0	10.5	18.5	30.5	46.0	65.0	86.0		
	Pv - Ph	31.4	62.9	137.4	202.1	262.9	319.6	374.1		
2	ϵ	1.01	1.53	2.25	2.78	3.14	3.50	3.78	3.24	23.8
	Ph	9.0	13.5	24.0	37.5	53.5	72.0	93.5		
	Pv - Ph	30.4	64.8	131.5	194.5	254.7	311.7	365.6		
3	ϵ	1.29	1.54	2.06	2.55	2.99	3.40	3.76	3.23	25.5
	Ph	7.5	10.5	19.5	32.5	48.5	67.0	87.5		
	Pv - Ph	31.8	67.8	136.4	200.1	260.1	317.3	371.9		
4	ϵ	0.89	1.25	1.90	2.42	2.83	3.11	3.43	3.18	24.9
	Ph	7.0	10.0	18.5	30.5	48.0	69.5	94.0		
	Pv - Ph	32.4	68.6	137.6	202.4	261.1	316.0	366.8		
Avg.	ϵ	1.06	1.46	2.07	2.58	2.98	3.32	3.64	3.22	25.1
	Ph	7.9	11.1	20.1	32.8	49.0	68.4	90.2		
	Pv - Ph	31.5	66.0	135.7	199.8	259.7	316.2	369.6		

ϵ = Per cent strain, P_h = Lateral pressure, $P_v - P_h$ = Deviator stress.

TABLE 10

Stabilometer Test Results — Mixture A

Initial Displacement = 4.00 — Coated Specimens

Test No.	Property	Strain, Lateral Pressure, Deviator Stress at Incremental Loads							Final Displ.	Hveem Stability
		500	1000	2000	3000	4000	5000	6000		
1	ϵ	1.05	1.49	2.06	2.62	3.15	3.59	3.96	4.42	24.1
	Ph	6.5	8.5	14.0	23.0	37.0	54.5	74.5		
	Pv - Ph	33.0	69.9	141.9	209.4	271.2	328.9	383.9		
2	ϵ	1.21	1.69	2.34	2.90	3.38	3.83	4.19	4.22	22.6
	Ph	7.0	9.5	16.5	27.0	42.0	61.0	82.0		
	Pv - Ph	32.3	68.7	138.9	204.7	265.5	321.6	375.3		
3	ϵ	1.21	1.62	2.31	2.91	3.44	3.88	4.25	4.22	23.0
	Ph	7.0	9.5	16.5	27.5	42.0	60.0	80.0		
	Pv - Ph	32.3	68.8	138.9	204.2	265.2	322.3	377.0		
4	ϵ	1.17	1.69	2.33	2.93	3.42	3.82	4.18	4.25	22.1
	Ph	8.5	11.5	19.0	30.5	44.5	62.0	82.0		
	Pv - Ph	30.8	66.7	136.4	201.2	262.7	320.6	375.3		
5	ϵ	1.12	1.56	2.20	2.76	3.28	3.76	4.12	4.30	23.9
	Ph	7.0	9.5	15.5	24.5	38.0	56.5	78.0		
	Pv - Ph	32.3	68.8	140.1	207.5	269.7	326.4	379.7		
Avg.	ϵ	1.15	1.61	2.25	2.82	3.33	3.78	4.14	4.28	23.1
	Ph	7.2	9.7	16.3	26.5	40.7	58.8	79.3		
	Pv - Ph	32.1	68.6	139.2	205.4	266.9	324.0	378.2		

ϵ = Per cent strain, P_h = Lateral pressure, $P_v - P_h$ = Deviator stress.

TABLE 11

Stabilometer Test Results | Mixture A

Initial Displacement = 5.00 | Coated Specimens

Test No.	Property	Strain, Lateral Pressure, Deviator Stress at Incremental Loads							Final Displ.	Hveem Stability
		500	1000	2000	3000	4000	5000	6000		
1	ε	1.28	1.68	2.40	3.04	3.56	4.08	4.44	5.20	22.6
	Ph	7.0	9.0	14.0	22.0	34.0	50.5	69.5		
	Pv - Ph	32.3	69.3	141.3	209.5	273.0	331.2	386.8		
2	ε	1.17	1.65	2.30	2.98	3.59	4.11	4.52	5.34	21.4
	Ph	7.0	9.0	14.5	23.0	35.5	53.0	72.0		
	Pv - Ph	32.3	69.3	141.0	208.5	271.3	328.4	383.6		
3	ε	1.25	1.74	2.42	3.03	3.59	4.07	4.48	5.13	22.7
	Ph	7.0	9.5	15.5	24.0	36.0	51.5	69.5		
	Pv - Ph	32.3	68.7	139.8	207.5	270.8	330.2	386.4		
4	ε	1.05	1.49	2.14	2.86	3.39	3.87	4.23	5.20	23.4
	Ph	6.5	8.0	12.0	18.0	30.0	49.0	72.0		
	Pv - Ph	32.9	70.4	143.8	213.8	277.5	333.3	385.0		
5	ε	1.29	1.77	2.46	3.10	3.70	4.23	4.63	5.16	23.1
	Ph	6.5	8.5	12.5	19.5	32.0	50.0	71.5		
	Pv - Ph	32.8	69.6	142.7	211.8	274.5	330.8	383.7		
Avg.	ε	1.21	1.67	2.34	3.00	3.57	4.07	4.46	5.21	22.6
	Ph	6.8	8.8	13.7	21.3	33.5	40.8	70.9		
	Pv - Ph	32.5	69.5	141.4	210.2	273.4	330.8	385.1		

ϵ = Per cent strain, P_h = Lateral pressure, $P_v - P_h$ = Deviator stress.

TABLE 12

Stabilometer Test Results — Mixture B

Initial Displacement = 1.00 — Coated Specimens

Test	Lateral Pressure, at Incremental Loads							Final	Hveem
No.	500	1000	2000	3000	4000	5000	6000	Displ.	Stability
1	8.5	15.5	32.0	51.0	71.0	92.0	115.5	1.23	37.6
2	10.5	20.0	40.5	62.0	84.0	107.0	132.0	1.26	32.6
3	8.5	14.0	27.5	43.5	61.0	80.0	102.5	1.16	43.3
4	10.0	18.0	34.0	50.5	68.5	87.0	107.5	1.31	37.8
5	10.0	16.0	29.5	46.0	64.5	84.0	105.5	1.18	41.4
6	10.5	19.5	39.0	58.5	80.5	102.0	125.5	1.27	33.8
7	8.0	12.0	32.0	48.0	66.0	88.0	111.0	1.18	40.0
8	10.0	18.0	40.0	65.0	89.0	113.0	138.0	1.18	32.3
9	10.0	17.0	35.0	55.0	75.0	98.0	121.0	1.20	36.3
Avg.	9.6	16.7	34.4	53.3	73.3	94.5	117.6	1.22	37.2

TABLE 13

Stabilometer Test Results — Mixture B

Initial Displacement = 2.00 — Coated Specimens

Test	Lateral Pressure at Incremental Loads							Final	Hveem
No.	500	1000	2000	3000	4000	5000	6000	Displ.	Stability
1	7.5	11.0	20.0	32.0	49.0	68.0	86.5	2.35	31.6
2	8.0	12.0	20.5	33.0	49.5	69.0	91.0	2.32	31.4
3	7.0	9.5	16.0	25.0	39.0	57.0	79.5	2.41	35.7
4	7.0	10.0	18.0	31.0	47.5	68.0	91.0	2.35	31.6
5	7.0	10.0	19.0	26.0	39.0	56.0	75.5	2.30	37.2
6	6.5	9.0	16.0	26.5	42.0	62.0	86.0	2.25	35.0
7	6.5	9.0	15.0	23.5	37.0	55.0	78.0	2.17	39.1
8	7.5	10.0	17.0	25.5	38.0	55.0	76.0	2.18	37.5
9	7.5	11.0	19.5	30.0	45.0	63.5	84.5	2.26	34.3
Avg.	7.2	10.2	17.9	28.1	42.9	61.5	83.1	2.29	34.8

TABLE 14

Stabilometer Test Results — Mixture B

Initial Displacement = 3.00 — Coated Specimens

Test	Lateral Pressure at Incremental Loads							Final	Hveem
No.	500	1000	2000	3000	4000	5000	6000	Displ.	Stability
1	6.5	8.5	14.0	21.5	34.0	50.0	69.5	3.24	32.4
2	7.0	10.0	15.5	23.5	36.0	53.0	73.0	3.16	31.5
3	7.0	10.0	16.0	23.5	35.0	50.5	70.0	3.25	32.1
4	6.0	8.0	12.5	18.5	29.0	44.0	63.5	3.33	35.4
5	6.5	8.5	13.0	19.0	29.0	43.5	63.0	3.32	35.1
6	6.5	8.5	12.5	18.5	29.0	44.0	64.0	3.26	35.5
7	6.5	8.0	12.0	18.0	27.0	41.0	59.5	3.24	37.5
8	6.5	8.0	12.5	18.5	28.0	42.5	61.0	3.22	36.7
9	6.0	8.0	12.5	19.0	29.0	43.0	63.0	3.25	36.2
Avg.	6.5	8.6	13.4	20.0	30.7	45.7	65.2	3.25	34.7

TABLE 15

Stabilometer Test Results — Mixture B

Initial Displacement = 4.00 — Coated Specimens

Test	Lateral Pressures at Incremental Loads							Final	Hveem
No.	500	1000	2000	3000	4000	5000	6000	Displ.	Stability
1	6.0	8.5	12.5	18.5	28.5	43.0	61.5	4.46	29.3
2	6.5	8.0	12.0	17.5	26.5	40.5	60.0	4.31	31.4
3	6.0	8.0	12.0	18.0	28.5	43.5	63.5	4.27	29.9
4	6.5	8.5	13.0	19.0	29.0	44.0	63.5	4.29	29.5
5	6.0	7.5	11.5	16.5	25.5	39.5	58.5	4.23	32.3
6	6.0	7.5	10.5	15.0	22.0	35.0	53.0	4.42	34.4
7	6.0	7.0	11.0	16.0	24.0	38.0	56.0	4.29	33.0
8	6.5	8.0	11.5	16.0	22.0	34.5	52.0	4.29	35.4
9	6.5	8.0	13.0	19.0	29.0	44.0	63.0	4.34	29.3
Avg.	6.2	7.9	11.9	17.3	26.1	40.2	59.0	4.32	31.6

TABLE 16

Stabilometer Test Results — Mixture B

Initial Displacement = 5.00 — Coated Specimens

Test	Lateral Pressure at Incremental Loads							Final	Hveem
No.	500	1000	2000	3000	4000	5000	6000	Displ.	Stability
1	6.0	7.0	9.5	13.5	20.5	34.5	53.5	5.33	30.6
2	6.0	7.0	9.0	12.5	20.0	32.5	50.0	5.27	32.3
3	6.0	7.0	10.0	14.0	20.5	33.5	52.0	5.34	31.3
4	6.0	7.0	9.5	13.5	20.0	31.0	49.0	5.32	33.2
5	6.0	7.0	10.0	14.5	22.0	36.0	55.0	5.43	29.3
6	6.0	7.5	10.0	13.5	20.0	31.0	49.0	5.41	32.9
7	6.0	7.5	11.0	16.0	23.5	35.0	52.0	5.27	30.5
8	6.0	7.0	9.5	13.0	18.5	30.0	49.0	5.18	34.6
9	6.0	7.0	10.0	14.5	22.0	34.5	53.0	5.36	30.5
Avg.	6.0	7.1	9.8	13.9	20.8	33.1	51.4	5.32	31.7

TABLE 17

Stabilometer Test Results | Mixture C.

Initial Displacement = 1.00 | Coated Specimens

Test No.	Lateral Pressure at Incremental Loads							Final Displ.	Hveem Stability
	500	1000	2000	3000	4000	5000	6000		
1	7.0	9.0	13.5	19.0	25.0	33.5	44.0	1.15	68.0
2	7.5	10.5	16.0	22.5	31.0	41.0	53.0	1.11	63.7
3	7.5	9.5	15.5	21.0	29.0	38.0	50.0	1.12	65.5
4	7.5	10.0	16.0	23.5	33.5	45.0	59.0	1.09	61.7
5	8.0	10.0	16.5	24.0	35.0	48.0	64.0	1.08	60.2
Avg.	7.5	9.8	15.5	22.0	30.7	41.1	54.0	1.11	63.8

TABLE 18

Stabilometer Test Results | Mixture C

Initial Displacement = 2.00 | Coated Specimens

Test No.	Lateral Pressure at Incremental Loads							Final Displ.	Hveem Stability
	500	1000	2000	3000	4000	5000	6000		
1	6.0	7.5	9.5	12.0	14.5	18.0	22.5	2.08	69.4
2	6.0	7.5	10.0	12.5	16.0	20.0	26.5	2.07	67.1
3	6.0	7.5	10.0	12.5	15.5	18.5	22.5	2.09	68.6
4	6.0	7.0	9.5	11.5	14.0	17.0	21.0	2.14	70.0
Avg.	6.0	7.4	9.8	12.1	15.0	18.4	23.1	2.10	68.8

TABLE 19

Stabilometer Test Results

Mixture C

Initial Displacement = 3.00

Coated Specimens

Test No.	Lateral Pressure at Incremental Loads							Final Displ.	Hveem Stability
	500	1000	2000	3000	4000	5000	6000		
1	5.5	6.0	7.5	8.5	10.0	12.0	14.0	3.09	69.6
2	5.5	6.0	7.5	8.5	10.0	12.0	14.0	3.12	69.5
3	6.0	6.5	8.0	9.5	10.5	12.5	15.5	3.09	69.0
Avg.	5.7	6.2	7.7	8.8	10.2	12.2	14.5	3.10	69.4

TABLE 20

Stabilometer Test Results | Mixture C

Initial Displacement = 4.00 | Coated Specimens

Test	Lateral Pressure at Incremental Loads							Final	Hveem
No.	500	1000	2000	3000	4000	5000	6000	Displ.	Stability
1	5.5	6.0	7.0	8.0	8.5	10.0	12.0	4.12	67.9
2	5.5	6.0	7.0	8.0	9.5	11.0	13.5	4.16	67.5
3	5.5	6.0	7.0	8.0	9.0	10.0	12.0	4.04	68.4
Avg.	5.5	6.0	7.0	8.0	9.0	10.3	12.5	4.11	67.9

TABLE 21

Stabilometer Test Results — Mixture C

Initial Displacement = 5.00 — Coated Specimens

Test No.	Lateral Pressures at Incremental Loads							Final Displ.	Hveem Stability
	500	1000	2000	3000	4000	5000	6000		
1	5.5	6.0	6.5	7.5	8.0	9.0	10.0	5.09	65.5
2	5.5	6.0	6.5	7.5	8.0	9.0	10.5	5.11	65.4
3	5.5	6.0	7.0	8.0	8.5	9.5	11.0	4.90	65.2
Avg.	5.5	6.0	6.7	7.7	8.2	9.2	10.5	5.05	65.4

TABLE 22

Stabilometer Test Results — Mixture D

Initial Displacement = 2.00 — Coated Lateral Surfaces

Test No.	Property	Strain, Lateral Pressure, Deviator Stress at Incremental Loads: 500	1000	2000	3000	4000	5000	6000	Final Displ.	Hveem Stability
1	ε	1.32	2.14	3.05	3.75	4.37	4.94	----	3.07	9.5
	Ph	13.0	27.0	57.0	90.0	126.0	164.0	----		
	Pv - Ph	26.2	50.9	97.2	139.7	178.4	214.2	----		
2	ε	1.27	2.04	2.98	3.68	4.25	4.78	5.23	3.11	10.0
	Ph	12.0	24.0	53.0	87.0	121.0	156.0	199.0		
	Pv - Ph	27.3	53.9	101.3	142.9	183.6	222.8	253.5		
3	ε	1.31	2.08	3.02	3.71	4.33	4.81	5.26	3.06	11.2
	Ph	10.5	22.0	50.0	78.0	110.0	146.0	182.0		
	Pv - Ph	28.8	55.9	104.3	151.9	194.4	232.5	270.1		
Avg.	ε	1.30	2.09	3.02	3.71	4.32	4.84	5.24	3.08	10.2
	Ph	11.8	24.3	53.3	85.0	119.0	155.3	190.5		
	Pv - Ph	27.4	53.6	100.9	144.8	185.5	223.2	261.8		

ε = Per cent Strain, P_h = Lateral Pressure, $P_v - P_h$ = Deviator Stress.

TABLE 23

Stabilometer Test Results — Mixture D

Initial Displacement = 2.00 — Coated Ends and Lateral Surfaces

Test No.	Property	Strain, Lateral Pressure, Deviator Stress at Incremental Loads							Final Displ.	Hveem Stability
		500	1000	2000	3000	4000	5000	6000		
1	ϵ	1.21	1.90	2.87	3.52	4.08	4.61	5.09	3.19	11.1
	Ph	13.0	26.0	53.0	84.0	115.0	148.0	183.0		
	Pv - Ph	26.3	52.1	101.6	146.2	190.3	231.4	270.2		
2	ϵ	1.14	1.79	2.72	3.41	3.98	4.42	4.95	3.06	11.3
	Ph	10.0	22.0	50.0	80.0	112.0	145.0	175.0		
	Pv - Ph	29.3	56.1	104.8	150.6	193.6	235.2	278.9		
3	ϵ	1.30	2.00	2.89	3.54	4.11	4.64	5.13	2.93	11.3
	Ph	10.5	22.5	50.0	80.0	115.0	149.0	184.0		
	Pv - Ph	28.8	55.4	104.6	150.2	190.1	230.4	268.8		
Avg.	ϵ	1.22	1.90	2.83	3.49	4.06	4.56	5.06	3.06	11.2
	Ph	11.2	23.5	51.0	81.3	114.0	147.3	180.7		
	Pv - Ph	28.1	54.5	103.7	149.0	191.3	232.3	272.6		

ϵ = Per cent Strain, P_h = Lateral Pressure, $P_v - P_h$ = Deviator Stress.

APPENDIX C

STATISTICAL COMPARISON OF MEAN STABILITY VALUES FOR SPECIMENS OF MIXTURE D, WITH AND WITHOUT COATED ENDS

APPENDIX C

STATISTICAL COMPARISON OF MEAN STABILITY VALUES FOR SPECIMENS OF MIXTURE D, WITH AND WITHOUT COATED ENDS

Coated Ends	Unaltered Ends
$n_1 = 3$	$n_2 = 3$
$X_1 = 11.1, 11.3, 11.3$	$X_2 = 9.5, 10.0, 11.2$
$\bar{X}_1 = 11.233$	$\bar{X}_2 = 10.233$
$S_1^2 = 0.013$	$S_2^2 = 0.774$

Testing for equality of variances,

$H_o: \sigma_1^2 = \sigma_2^2$ $\qquad \alpha = .05$

$H_1: \sigma_1^2 < \sigma_2^2$ $\qquad f_1 = f_2 = 2$

$$\frac{S_1^2}{S_2^2} = 59.538$$

$$F_{(.05,\ 2,\ 2)} = 10.000 < 59.538$$

Reject H_o and conclude that $\sigma_1^2 < \sigma_2^2$ at 5% level of significance.

Comparing mean stability values,

$H_o : \mu_1 = \mu_2$ $\qquad \alpha = .05$

$H_1 : \mu_1 > \mu_2$

$$f = \frac{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2}{\frac{\left(\frac{S_1^2}{n_1}\right)^2}{n_1+1} + \frac{\left(\frac{S_2^2}{n_2}\right)^2}{n_2+1}} - 2 = 2.13$$

$$t = \frac{(\bar{X}_1 - \bar{X}_2) - (\mu_1 - \mu_2)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} = 1.99$$

$$t(.05, 2.13) = 2.43 > 1.99$$

Accept H_o and conclude that $\mu_1 = \mu_2$ at 5% level of significance.